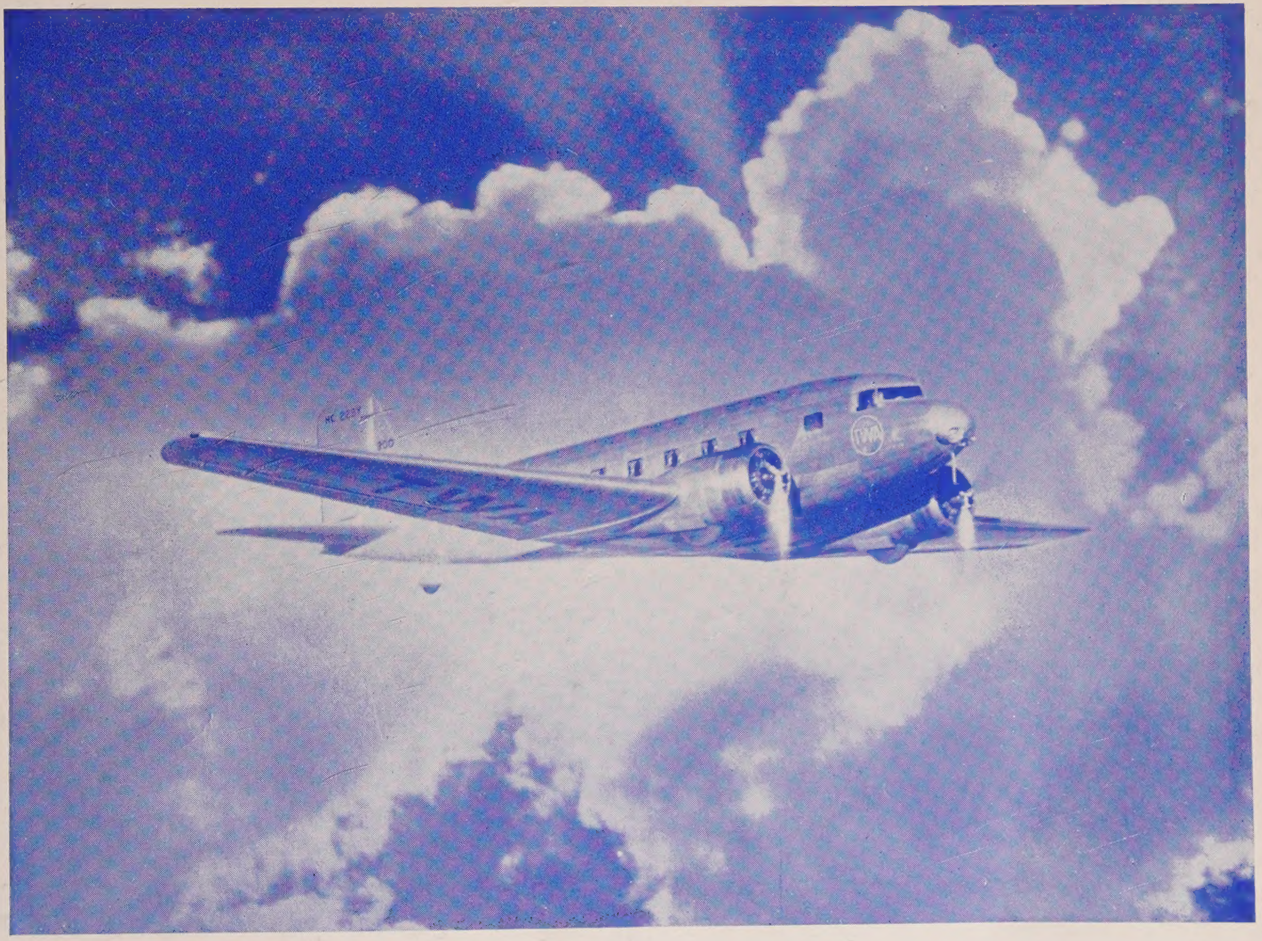
Electrical Engineering

February
1934



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This Month—

Front Cover

New all-metal TWA airliner takes to the skies. For further description of this plane see p. 349.

Special Educational Series—3

Special Articles

A.I.E.E. Papers

A Science Series for Engineers

NOW appearing month-by-month in ELECTRICAL ENGINEERING is a series of articles written by some of the foremost authorities in several of the more important and rapidly advancing fields of science that are of special significance to electrical engineers. The original idea was suggested by Prof. Vladimir Karapetoff of Cornell University who urged the preparation and publication of "a series of short articles in ELECTRICAL ENGINEERING for the guidance of ambitious young engineers who wish to prepare themselves for the newer problems (to be met) after the recovery from the present depression." Taken under advisement by the A.I.E.E. committee on education this suggestion was developed through the active coöperation of many interested parties. The result of more than a year of thoughtful planning, development, and coördination, and presenting the generous contributions of some of the highest recognized authorities, this series of articles aptly has been called a post-college course in contemporary science.

The first article in the series was published in November 1933 issue of ELECTRICAL ENGINEERING; the second in the January 1934 issue; the third begins on the facing page. Each of the authors generously has promised his full coöperation in the preparation of subsequent manuscripts which will be fully up-to-date as published. The complete program is listed in the following tabulation, which includes the title of the paper and the actual or scheduled publication date, followed by a short biographical sketch of the author:

Theory of Probability — **Nov. 1933**

ALBERT ARNOLD BENNETT—Mathematician. Professor of mathematics at Brown Univ., Providence, R. I., since 1927; born Yokohoma, Japan, June 2, 1888; A.B. Brown Univ. 1910, A.M. and M.S. 1911; Ph.D. Princeton 1914; instructor in mathematics at Princeton 1914–16; adjunct professor Univ. of Texas 1916–18, associate professor 1918–25; professor and head of the department Lehigh Univ., 1925–27. Mathematician and dynamic expert ordnance dept., U.S. Army 1919–22. Member of Am. Math. Soc. and Math. Assoc. of Am.

Fundamental Properties of the Electron — **Jan. 1934**

ALAN TOWER WATERMAN—Physicist. Associate professor of physics at Yale Univ., New Haven, Conn., since 1930; born Cornwall-on-Hudson, N. Y., June 4, 1892; A.B. Princeton 1913; A.M. 1914, Ph.D. 1916; instructor in physics at Cincinnati 1916–17; lieutenant, meteorological section U. S. A. Signal Corps, 1917–19; instructor in physics Yale Univ. 1919–23; associate professor 1923–30; fellow Am. Phys. Soc.

Electric Discharges in Gases; Ionization and Excitation — **Feb. 1934**

LEWI TONKS—Physicist. Research physicist, General Elec. Co., Schenectady, N. Y.; born New York, N. Y., Dec. 13, 1897; B.S. Columbia Univ. 1917, assistant in physics 1915–18; special government expert New London, Conn. 1918–19; Ph.D. Columbia Univ. 1924; member Am. Phys. Soc.

Electric Discharges in Gases; Scattering Drift and Diffusion of Ions — **March 1934**

KARL KELCHNER DARROW—Physicist. Member, technical staff, Bell Tel. Labs. Inc. since 1925; born Chicago, Ill., Nov. 26, 1891; B.S. Univ. of Chicago 1911, Ph.D. 1917; physicist Western Elec. Company 1917–24; summertime professor Stanford Univ. 1929, Univ. of Chicago 1931, Columbia Univ. 1932; member of Am. Phys. Soc., Optical Soc. of Am., Physik. Gesell., Soc. de Physique.

Electric Discharges in Gases; Arcs and Glows — **April 1934**

JOSEPH SLEPIAN—Physicist, Electrical Engineer. Consulting research engineer Westinghouse Elec. and Mfg. Co., since 1916; born Boston, Mass., Feb. 11, 1891; A.B. Harvard 1911, A.M. 1912, Ph.D. 1913; instructor Cornell Univ. 1914–15; Fellow A.I.E.E.
RURIC COIN MASON—Co-author with Doctor Slepian. Since 1924 with Westinghouse Elec. and Mfg. Co.; born Bentonville, Ark., Sept. 6, 1903; B.S. Univ. of Ark. 1924; Associate A.I.E.E.

Structure of Atoms and Molecules; Electronic Theory of Valence — **May 1934**

MAURICE LOYAL HUGGINS—Chemist. Associate, dept. of chemistry, The Johns Hopkins Univ.; born Berkeley, Calif., Sept. 19, 1897; A.B., B.S. Univ. of Calif. 1919, M.S. 1920, Ph.D. 1922; instructor in chemistry Stanford Univ. 1925–26, assistant professor 1926–33; member Am. Chem. Soc., fellow Am. Phys. Soc.

Thermionics — **July 1934**

SAUL DUSHMAN—Physical Chemist. Assistant director General Elec. research laboratory since 1928; born Rostov, Russia, July 12, 1883; A.B. Univ. of Toronto 1904, demonstrator in electrochemistry 1904–09, lecturer 1909–12, Ph.D. 1912; with the Gen. Elec. research lab. since 1912; member Am. Phys. Soc., Am. Chem. Soc., Optical Soc. of Am., associate A.I.E.E., naturalized citizen of the United States since 1917.

Photoelectricity — **Aug. 1934**

ARTHUR LLEWELYN HUGHES—Physicist. Head of the department of physics at Washington (St. Louis) Univ. since 1923; born Liverpool, Eng., December 18, 1893; Oliver Lodge fellow, Liverpool, B.S. 1906, D.Sc. 1912, A.B. Cambridge 1910; assistant demonstrator in physics in Cavendish Lab. (Cambridge), assistant professor of physics at Rice Inst., research professor at the Queens Univ. (Canada) 1919–23; member Am. Phys. Soc.

Recent Theories of Magnetism — **Sept. 1934**

FRANCIS BITTER—Electrical Engineer. Research engineer Westinghouse Elec. and Mfg. Co. since 1930; born Weehauken, N. J., July 22, 1902; A.B. Columbia Univ. 1924, Ph.D. 1928; National Research Council fellow Princeton Univ., and Calif. Inst. of Tech. 1928–30; member Am. Phys. Soc.

Operational Calculus — **Oct. 1934**

MURRAY FRANK GARDNER—Electrical Engineer. Assistant professor, electrical engineering, Mass. Inst. of Tech., since 1929; born Lansing, Mich., Dec. 17, 1897; B.S. Univ. of Mich. 1920, M.S. M. I. T. 1924; electrical engineer, cable works, Am. Steel and Wire Co., Worcester, Mass., 1922–23; instructor in electrical engineering in M. I. T. 1923–29; Associate A.I.E.E.

X Rays — **Nov. 1934**

GEORGE LINDENBERG CLARK—Chemist. Professor of chemistry, Univ. of Ill. since 1928; born Anderson, Ind., Sept. 6, 1892; A.B. DePauw Univ. 1914; M.S. Univ. of Chicago 1914, Ph.D. 1918; instructor in chemistry DePauw 1914–16; professor of physical chemistry, Vanderbilt, 1919–21; National Research Council fellow, Harvard Univ. 1921–24; assistant professor of applied chemical research, Mass. Inst. of Tech. 1924–27; associate professor of chemistry at the Univ. of Ill. 1927–28; member Am. Chem. Soc., fellow Am. Phys. Soc., fellow Royal Soc. of Arts, member Physik. Gesell.

Fundamental Electrical Properties of Mercury Vapor and Monatomic Gases — **Dec. 1934**

ALBERT WALLACE HULL—Physicist. Assistant director General Elec. research lab. since 1928; born Southington, Conn., April 19, 1880; A.B. Yale Univ. 1905, Ph.D. 1909; instructor in physics, Worcester Poly. Inst. 1909–12, assistant professor 1912–14; research physicist for the Gen. Elec. Co. since 1914; D.Sc. Union Col. (Schenectady) 1930; awarded Potts' medal by Franklin Inst. 1923 for work on X ray crystal analysis; Morris Liegmann prize 1930 for work on vacuum tubes; member Am. Phys. Soc.

Mapping of Fields — **Jan. 1935**

ERNST WEBER—Research Engineer. Research professor of electrical engineering at Poly. Inst. of Brooklyn, N. Y., since 1930; born Vienna, Austria, Sept. 6, 1901; Dipl. Ing. 1923 and Dr. of technical science 1927, Poly. Inst. of Vienna; Ph.D. 1925, Univ. of Vienna; research engineer Siemens-Schuckert Werke A.G., Vienna, 1924–29 and Berlin, 1929–30; associate professor Poly. Inst. of Berlin 1929–30; member Vienese Inst. of Elec. Engrs.; Berlin Inst. of Elec. Engrs.; Berlin Soc. for App. Math. and Mech.; Am. Phys. Soc.; Associate A.I.E.E.

Electric Discharges in Gases

Ionization and Excitation

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In view of the widespread occurrence and the current technical importance of the various manifestations of free electricity in gases, this article appropriately reviews current knowledge concerning the nature of such free charges, how they arise from the normally uncharged atoms and molecules of a gas, and their relation to light radiation. This is the third in a series of special articles developed under the sponsorship of the A.I.E.E. committee on education, and the first of three that will deal with the major divisions of the general subject of electric discharges in gases; the second will deal with the laws governing the movement of free charges through a gas, and the third will discuss known types of discharges in the light of the basic processes which by that time will have been set forth in these columns.—Editor

ELECTRIC CHARGES free to move in a gas give rise in their wild state to some of nature's most splendid spectacles. Tamed, controlled, and harnessed in new and "unnatural" ways, these same entities have been put to work as part of man's host of inanimate servants. Untamed there are the ionized layers of the atmosphere, which, as the Heaviside Layer, were assumed in the first place to explain long distance radio transmission. There is lightning with its puzzling off-shoot, ball lightning, and there is the aurora borealis. The very air we breathe contains free electricity which has definite physiological effects. Tamed, we have mercury vapor and other similar lamps, mercury arc rectifiers, and certain protective devices against lightning. Only half tamed are the phenomena in circuit breakers of many kinds, commutator sparking, and corona. The widespread occurrence and technical importance of the various manifestations of free electricity in gases are evident.

The treatment of this subject lends itself to division into 3 parts. The first, which the present article will survey, is concerned with the nature of the free charges, how they arise from the normally uncharged atoms and molecules of a gas, and their relation to light radiation. The second division will deal with the laws governing the movement of the free charges through the gas, and the third will discuss known types of discharges in the light of the basic processes which by that time will have been set forth in this series of articles as published in ELECTRICAL ENGINEERING.

Basic Concepts

All matter is made up of atoms, and every atom has a positively charged nucleus at the core around which are grouped enough electrons to contribute an equal negative charge. Thus any disruption of an atom yields charged particles which can carry electricity under the influence of an electric field. The simplest of such particles is the electron. More complicated are atoms or molecules lacking one or more electrons. These constitute the simpler positive ions. Electrons can join neutral atoms or molecules to give simple negative ions. More complex are clusters of atoms and molecules held in union by the electron deficiency or excess of one of them. All these are ions, but, as experiment indicates that in technical applications up to the present only electrons and simple positive ions are important, the word ion will be used in this article to designate the latter, and ionization will refer to the corresponding atom-splitting or molecule-splitting process.

A fundamental fact about ionization is that to ionize a normal atom a definite characteristic amount of energy must be supplied to it. In what forms and by what agencies this is accomplished, and what other phenomena accompany the transfer we proceed to inquire.

When electrons of known and controllable speed are shot into the gas under investigation, no ions appear until a definite minimum value is exceeded. The elements of the experimental apparatus by which this value first was conclusively determined by Davis and Goucher in 1917 are shown in Fig. 1. Electrons from the hot filament C were accelerated by the electric field between it and the gauzes G (the potential distribution is indicated by the fine continuous line) so that when they passed into the GH space they had a kinetic energy eV, e being the electronic charge and V the potential increase between C and G. Parenthetically it may be noted that this voltage rather than the more orthodox energy units can serve as a measure of energy, and that it is so used under the designation *electron volt* or *equivalent volt*. Some of the electrons traversing the GH region collided with gas atoms there, the rest passed into the opposing field in HP (for the moment, suppose J to be absent) which is sufficient to turn them back. Thus P could receive no electron current, but ions, freed by

collisions between G and H, could flow to it and be registered by the galvanometer. It was recognized at the time that such experiments were first performed that radiation capable of ejecting electrons from the metallic electrodes might also arise in these collisions, and that such electrons originating at P would be indistinguishable from the ions reaching P. By inserting the additional gauze J Davis and Goucher were able definitely to separate the 2 effects. The ions were able to penetrate the adverse field between

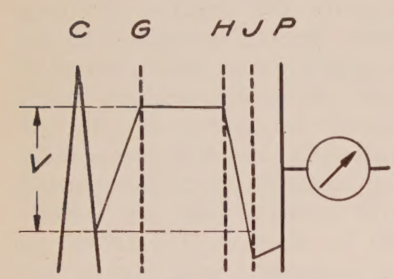

Fig. 1. Elements of apparatus for determining ionization potentials

J and P by virtue of the momentum acquired between H and J, but the photoelectrons from P had insufficient energy to overcome this same field and consequently they fell back to P again. Ionization was found to set in abruptly at a certain voltage. This is the ionization potential of the gas, and accordingly is its dissociation energy in electron volts. At other voltages radiation set in abruptly. Taken together, all these potentials are called *critical potentials*. Some values will be given later.

The *modus operandi* of this classical experiment is not always as simple as the foregoing description would indicate. Some of the complications are inherent in the design of the apparatus, some in the nature of the atom. Other methods have given results consistent with this early one, and have helped in disentangling the intricacies, particularly those connected with the light emission from impacted atoms. To understand the many interrelated phenomena one requires a working model of the atom. Quantum theory, devised originally by Planck to explain certain discrepancies in radiation theory, has been expanded fruitfully to cover atomic properties by the contributions of Bohr, de Broglie, Born, Schroedinger, Heisenberg, and Dirac—to mention only a few of the most outstanding. The fundamental principle of quantum theory is that light has a corpuscular as well as a wave aspect. Each corpuscle or photon carries a definite amount of energy E which is equal to the frequency ν of the wave multiplied by Planck's constant, $h = 6.55 \times 10^{-27}$ erg sec; that is,

$$E = h\nu \tag{1}$$

Bohr, in 1913, made the hypothesis that in each atom there was a finite number of possible energy levels which depended, in the main, upon the relation of individual electrons to the rest of the atom.

When transition between 2 of these levels was accompanied by either the absorption or emission of light, the energy difference was related to the light frequency by eq 1. In this way, the lines of the spectrum were directly connected with the structure of the atom. Later additions to the theory have had to do with the question of which transitions can occur spontaneously, and with the calculation of the energy levels. It is in the latter field that the methods and concepts of wave mechanics, originating with Schroedinger in 1926, have been applicable. Crudely stated, this theory allows the calculation of the standing-wave states of the atom when the wave nature of the electrons is taken into account. Beyond this we do not have to go, as it suffices for us to know the energy levels, whether they have been empirically or theoretically determined. Figure 2 is a diagram of the lower energy levels of the mercury atom showing the energy differences and the wave lengths corresponding to them. The table gives a few critical potentials for some of the gases most commonly used in electrical discharges.

Interactions of Electrons and Photons With Atoms

The lower energy absorptions of which an atom is capable excite it by raising the outermost electron to levels of potential energy higher than it possesses in the normal atom, and this sequence of states terminates with the complete removal of that electron. Through excitation succeeded by ionization, a normal atom can be ionized by 2 or more smaller energy doses. There is, of course, a least energy which a normal atom can absorb, and experiment shows that under *certain conditions* ions appear when the energy of the impinging electrons exceeds this value. This is one of the complications which might have made difficulties in the Davis and Goucher experiment, but in practice did not. The reason is that the electron density and gas densities were so low that the yield from 2- or multiple stage processes was undetectable, although at higher concentrations this yield might be greater than that from single impacts.

The efficiency of ionization by electrons as well as the conditions for ionization must be considered. Two kinds are of importance. First, an electron traveling at a known constant velocity traverses a gas at a standard density and frees a certain number of ions (and electrons, of course) per unit length of path. Second, an electron with a known velocity is projected into a gas and releases a certain total number of ions while dissipating its whole kinetic energy. Each of these efficiencies is appropriate to special portions or types of actual discharges.

The former can be expressed in terms of an area, the effective cross section of the atom for single impact ionization. Suppose a slab of gas (thickness x) of not-too-great concentration (N atoms per unit volume), each atom of which has a vulnerable cross section σ, to be placed across a beam of electrons. The gas presents a target area for ionizing impact of σNx per unit area of slab. $N\sigma$ is, then, the number of ions freed per electron per unit length of path, and σ is the atomic property defining the yield. Below the ionizing voltage σ is zero; its course above begins with a steep rise to a broad maximum between 100 and 500 volts and then a steady decline as far as experiments have been carried—some 25,000 volts.

The curves for several gases are reproduced in Fig. 3. The ordinate is $N\sigma$, and N is roughly 3.27×10^{14}. The maximum values of σ are less than half the ordinary kinetic theory values based upon viscosity, equation of state, etc.

All the encounters do not result in singly charged ions. The increasing electron energies available are able to eject not only the most loosely bound electron, but also, successively, those held more tightly. Mercury ions bearing up to 5 elementary charges have been observed by Bleakney below 150 volts. At this potential doubly charged ions carry $^1/_2$ while Hg^{3+} carry 12 per cent of the current carried by Hg^+.

The second kind of efficiency increases continually with increasing energy. In those cases that have been tested, the complicated processes involved produce a rather simple result: For energies well above the ionizing potential, the number of ion pairs formed is proportional to the electron energy, and the actual number formed lies between $^1/_3$ and $^4/_5$ (depending on the gas) of the number which would be created if only the ionization potential was absorbed for each pair.

In our theoretical discussion radiation effects in the atom were anticipated. In the Davis and Goucher experiment such effects were demonstrated. The emission of light by atoms in reverting to lower energy levels, and the raising of atoms in these states to the higher levels by photons of the same frequencies, are linked by the principle of detailed balancing which asserts that the existence of an elementary process always signifies the possibility of the reverse process. In particular, the lowest frequency which a normal atom can absorb is its *resonance radiation*, and is connected through eq 1 with one of the critical potentials, which accordingly is called the resonance potential.

In this way photons are able to act the rôle of electrons. Resonance photons are able to produce ionization in a gas under certain conditions just like electrons at the lowest critical potential, but 3 important differences between electron and photon behavior are to be noted.

First, in one respect electrons are much more effective exciting agents, for their probability of excitation extends to many volts above the critical potential itself, whereas photons must carry exactly the proper energy. For instance, a Doppler effect broadening of a spectrum line, which might escape the eye, renders the extreme frequencies in the line useless for excitation.

Second, the kinetic energy of an electron is, for all practical purposes, irrevocably lost as such at an excitation. After 10^{-7} to 10^{-8} sec the atom ejects this energy as a photon. However, the light itself may be reborn many times through absorption, excitation, and reëmission. This is particularly true of resonance radiation for which a plentiful supply of excitable atoms exists. This phenomenon has been called *imprisonment of radiation*. Photons of the 2,536 resonance line of mercury have a mean free path of 0.12 cm in mercury vapor saturated at a temperature of 60 deg C. On the average, a photon starting at the center of a bulb 5 cm in radius would excite $(5/0.12)^2 = 1{,}700$ times. A duration of a single excitation of 10^{-7} sec would lead to a total time of existence of the energy in the gas of 1.7×10^{-4} sec. Actually, collisions of the second kind, discussed in the following paragraphs, prolong this time still more.

Third, electrons can cause transitions that photons cannot cause. Electrons of 4.66 volts can excite mercury atoms but 2,536 corresponding to 4.86 volts is the lowest frequency light that the atom will absorb. The principle of detailed balancing tells that the emission of radiation corresponding to 4.66 volts does not occur. This transition therefore is shown as a broken line in Fig. 2. In a case like this, where the so-called forbidden line is for a transition ending in the normal state, the excitation energy is trapped, and the atom is said to be in a *metastable state*. Whether the atom ever can revert spontaneously is not known; what is known is that the atom remains in such a state possibly hundreds of thousands of times as long as in other excited states, and certainly long enough so that other agencies can release it. Both imprisonment of radiation and the formation of metastable states are properties which permit the accumulation of large numbers of excited atoms from which transitions to higher levels can occur.

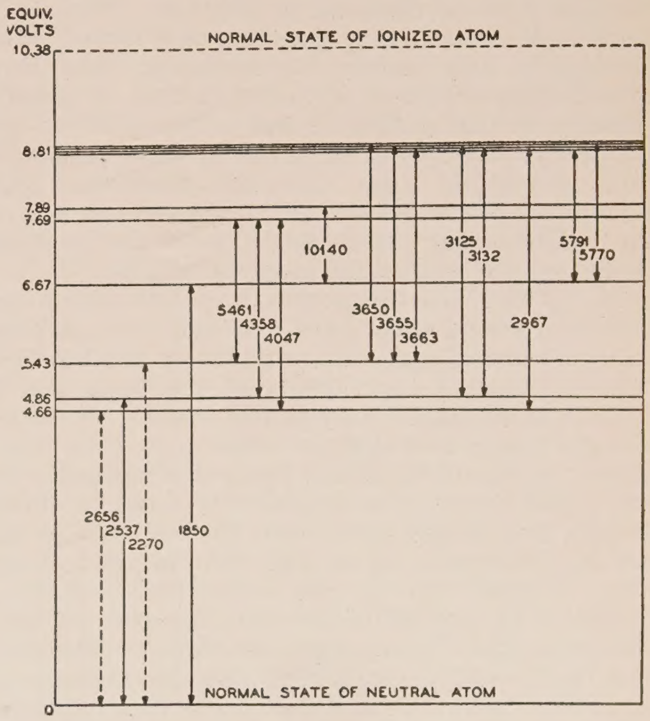

Fig. 2. Lower energy levels of the meicury atom

The numbers on the transition arrows give the wave length of the corresponding radiation in Angstrom units (10^{-8}cm)

Other Types of Energy Interchange

The energy of an excited atom can be transferred directly to other atoms by contact without the mediation of electrons or photons. The classical experiment was performed by Franck and Cario in 1922. There is no interaction between thallium

vapor and the 2,536 mercury line. An admixture of mercury vapor while 2,536 photons traversed the gas, resulted, however, in the emission of several lines of the thallium spectrum. The excited mercury atoms which collided with normal thallium transferred their pent-up energy, certainly leaving the thallium excited, and probably dividing the excess between the 2 atoms as kinetic energy. Contacts of this type, known as *collisions of the second kind*, have been observed in other cases and guessed at in many more.

A limiting case is that in which an ion and an atom of the same species interchange their charge, but not their kinetic energy. Actually, the immediate experimental evidence might as well indicate an exchange of kinetic energy and not of charge; but this view is inconsistent with an extrapolation from the known behavior where contact is between excited and normal atoms of the same species, or between ions and atoms of different species as the critical potentials approach equality. Actual proof probably is impossible, although theoretically an experiment with isotopes would be decisive.

The kinetic or radiation energy absorbed by a gas in the various processes that have been described is, of course, lost to the original energy beam, whether it be of electrons or photons. With electrons most of the energy goes into new forms; with photons it may merely be scattered. Watching what happens has been a fruitful method of investigation. Critical potentials have been observed by noting the decrease in electrons of full velocity as these potentials were exceeded. Resonance potentials are evidenced by the powerful absorption of the corresponding wave length from the incident beam and its reradiation in all directions.

The positive ion is another corpuscle which can have a profound effect upon an atom. It has been used to bombard gas atoms despite far greater difficulties attending experiments of this type and a corresponding uncertainty in the results. A series of experiments in which the noble gases were bombarded by ions of the alkalis prove that ionization by ion impact occurs, that roughly and with exceptions the ion that is most effective is the one next to the gas in the atomic series, and that in the voltage range studied—up to 800 volts—the ionization, beginning at from 100 to 300 volts, increases steadily with potential. In argon gas the efficiency of ionization of K^+ (potassium) at 700 volts lies between 50 and 100 per cent of that of electrons at their optimum velocity.

Just as excited atoms can transfer their excitation to others, it is possible for ions from atoms of higher ionization potential to ionize other kinds of atoms of lower ionization potential by contact, and the closer the ionization potentials lie, the more likely is the transfer. Helium and neon presumably are ionized in a definite relative proportion when a mixture is bombarded by electrons of fixed velocity. Harnwell tried increasing the opportunity for interchange of charge by simply raising the gas density. The Ne^+ increased relative to the He^+. The behavior of N_2^+ and N^+ has been found to be similar in other experiments, and the admixture of other gases has shown that the closer the ionization potentials of the contacting particles, the more likely is the interchange.

Neutral atoms of argon have been reported by Beeck as rather effective ionizing agents for argon. At the lowest velocity for which the design of his apparatus was suitable, about 50 volts, ions were generated in large numbers. Full details and further confirmation apparently have not yet been announced.

Fast electrons, such as beta rays, high frequency photons like X rays and gamma rays, high speed protons, alpha particles (He^{++}), and neutrons, originating in radioactivity or cosmicr adiation, all are ionizing agents. Their rôle is confined to the fortuitous or intentional initiation of an electrical discharge in certain cases where the voltages, pressures, etc., are adequate to maintain the current flow once it is started, but the first few free charges are lacking.

Finally, high temperature must be listed as a cause of ionization. In the ideal case of thermal equilibrium there exists a complete melange of kinetic energy, excited states, radiation, free ions, and free electrons, among which all the interchanges so far discussed are taking place equally in both directions. Saha has derived a relation between ionization potential, temperature, and the equilibrium constant for dissociation from thermodynamics that has been confirmed experimentally in many cases.

Charges Freed From Solids

The origin of free charges and radiation within the body of a gas is not, in general, the only source of electricity in a discharge. The glass or metallic

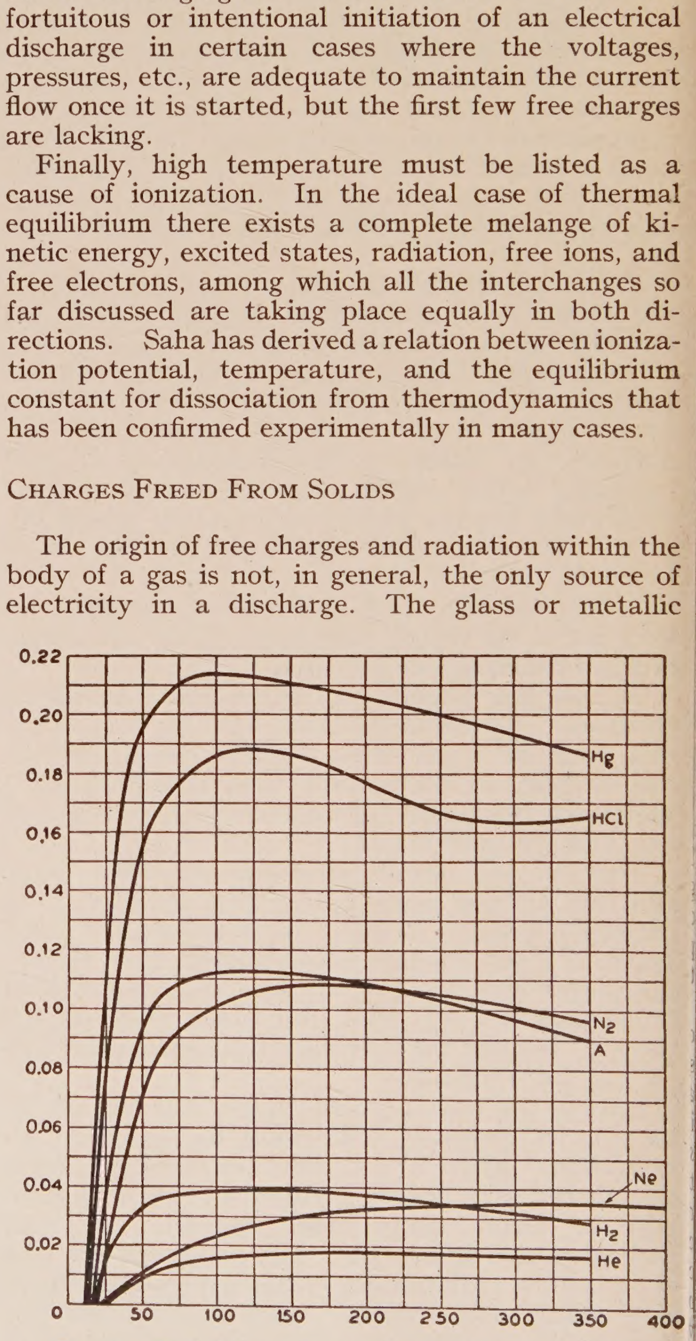

Fig. 3. Probability of ionization by electron impact

Number of elementary charges freed per centimeter of path at 1 mm pressure and room temperature plotted against the kinetic energy of the electrons in electron volts (Compton and Van Voorhis, "Phys. Rev.," v. 27, 1927, p. 724)

Table of Critical Potentials

Gas	Transition	Energy Difference—Volts
Mercury (Hg)	Metastable	4.66
	Resonance	4.86
	Ionization	10.36
	Hg^+ to Hg^{++}	19.0
Helium (He)	Metastable	19.77
	Ionization	24.5
Neon (Ne)	Metastable, Resonance	16.4 –16.7
	Ionization	21.5
Argon (A)	Ionization	15.69
Sodium (Na)	Resonance	2.10
	Ionization	5.12
Nitrogen (N)	N to N^+	14.5
	N_2 to N_2^+	16.0

confining walls and the electrodes by which current enters and leaves the conducting space often are necessarily and sometimes disconcertingly active in producing new charges.

Thermionic emission either of electrons or of ions from hot metals and compounds is well known and will be discussed in a later article of this series.

Electrons can be drawn from cold conductors by strong electric fields of magnitudes exceeding 10^5 volts per cm. As surface contamination is eliminated, the necessary field strengths become greater. A very marked aging effect of clean surfaces indicates that the emission usually has occurred at minute, but possibly sharp, surface irregularities which caused local increases of field strength. To avoid this unknown and variable field amplification Beams recently has applied high fields to a clean liquid mercury surface. Enough electrons were extracted with 1.8×10^6 volts per cm to start a discharge in the low pressure mercury vapor. Either an unsuspected cause of local concentrations of field is present, or theory needs revision, for this field is only $^1/_{18}$ that which the wave mechanics formula derived by Fowler and Nordheim indicates as necessary.

All the agencies of gas ionization also free electrons from metals. Some of them are known or suspected to act similarly on certain nonconductors, but often it is impossible to devise experiments to test this. The condition of a metal surface, whether it contains gas either absorbed or adsorbed, and the presence of minute traces of other surface contamination, particularly atoms of the alkalis, markedly affects the phenomena.

Electrons with energies of the order of hundreds of volts are able not only largely to escape themselves from metal targets on which they impinge, but also to eject additional electrons from the metal itself. The onset of this phenomenon, known as *secondary electron emission,* has been observed down to less than one volt. At the optimum an actual reversal of current approximating the incident current in magnitude can occur. Alkaline earth contamination enhances the effect. Certain cases of the conduction of electron currents in good vacuum through long glass tubes can be explained only on the hypothesis that the walls became and remained positively charged by the emission of secondary electrons from the glass.

In order for a photon to eject an electron from a conductor, its energy must exceed the work function φ of the surface. The corresponding frequency is the long wave length limit for photoelectric emission. The energy of the photon in excess of that absorbed in leaving the surface may appear as kinetic energy of the photoelectron. The maximum energy E_m of the latter therefore is given by the equation

$$E_m = h\nu - e\varphi$$

which was proposed by Einstein in 1905. X rays or ultra-violet light impinging on an electrode often are used to initiate a discharge. Differences between the voltage equivalent of the photoelectric threshold and the thermionic work function arise from contamination which is the more serious in causing deviations from clean surface values in the photoelectric case because the high temperatures necessary for thermionic emission tend to keep the surface clean. A surface film of oxygen increases the work function; surface films of the alkalis lower it. Efficiencies of one electron per 14 incident *quanta* have been observed.

Emission of electrons attending the impact of metastable atoms of helium (19.7 volts) on molybdenum and magnesium has been detected by Oliphant. Some electrons were found to possess as kinetic energy the full excess of the excitation energy over the work function of the metal. Various effects in arcs in the noble gases have been attributed to the release by metastable atoms of electrons from the electrodes and the glass walls, but the photoelectric effect seems now to have been the chief factor in several of these cases.

The ejection of electrons by fast moving ions is indubitable, but the experimental difficulties are such that comparatively little definitive work has been done, and the results of different experimenters cannot be compared. A ratio greater than unity of electrons emitted to helium ions impinging on cold contaminated molybdenum has been reported by Oliphant when the energy was greater than 800 volts. A constant relative yield of 0.2 was found for clean molybdenum all the way from 600 down to 100 volts. A helium ion carries enough potential energy not only to free from the metal the electron needed for its own neutralization, but also to eject another besides, and perhaps it is an effect of this kind rather than one caused by the kinetic energy that is operative here. These yields are tremendous compared to the few per cent found in certain other cases of ion impact.

A brief survey such as the foregoing can give only a certain superficial acquaintance with the field. Greater experimental detail and fuller discussion is to be found in such books as K. K. Darrow's "Electrical Phenomena in Gases" (Published by Williams and Wilkins, Baltimore, Md.) or the 2 volumes on the "Conduction of Electricity Through Gases" by J. J. and G. P. Thomson (Published by University Press, Cambridge, England). In German the "Handbuch der Physik" (Published by Julius Springer, Berlin), Vol. 23, chapters 5 and 7, covers some of the ground. In these books will be found the references to the original papers upon which present knowledge ultimately rests.

The Life of Impregnated Paper

A series of accelerated life tests on 14 different oils as used for the impregnation of one grade of cable insulating paper is described herein. Complete absence of gaseous ionization was insured in these tests. It is shown that there is a definite relationship between the life of impregnated paper under stress, and the capillary constant of the oil. With oils of one definite type, the life of the paper increases with penetrative power. Between oils of different types, there may be differences in the relation of penetrative power to life. The influence of dielectric loss on life is negligible, and the values of power factor during life tests appear to have no relation to life.

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IT IS generally agreed that the most important factor limiting the life of the so-called solid type of impregnated paper insulated cable is internal ionization in voids or gas pockets, commonly due to expansion and contraction under temperature cycles, or less commonly, to impregnation originally imperfect. Gaseous ionization leads to well-known rapid heating and destructive action on both oil and paper. Under its influence the original sealing action of the oil is lost, and the original paper structure is destroyed, both in such mutually cumulative relation as to lead rapidly to breakdown.

Efforts to increase the life of such cables therefore have been of 2 general types: (1) the search for materials which will withstand gaseous ionization without injury; and (2) the suppression or elimination of ionization.

In the first type of effort an enormous amount of work and expenditure of money has been directed to studies of wax formation, ionic bombardment, and allied phenomena in oils and in oil mixtures, in search for a compound which is most nearly proof against the action of ionization. Apparently the point of view in these studies is that gaseous ionization is necessarily inherent in the solid cable and that it should be possible to discover materials which are not damaged thereby. It cannot be said that the results of this large amount of work have been very encouraging. Some knowledge has been acquired as to the probable causes of wax formation and some differences in the behavior of various oils have been found. No compound of outstanding resistance to ionization has been found, however, nor in view of the inherent chemical instability of oil and the susceptibility of paper fiber to oxidation can it reasonably be expected that a radical improvement will be found in this direction.

Far more promising, however, are the results attained in the suppression and elimination of internal gaseous ionization. The most obvious measures are the restriction of voltage stress and temperature elevation to such values as, based upon practice and experiment, are certain to limit the intensity of ionization to such values as will permit a reasonable life of the cable. These are the measures commonly adopted for solid cables and they have therefore imposed definite limitations upon their capacities and voltage ratings.

Next in order of importance as limiting ionization is the shielded or type *H* cable. This improvement is based upon sound principles since it limits the volume of insulation exposed to ionization without interference with the normal insulating function, and at small cost. It does not, however, attack the essential limitation of the solid cable, namely the occurrence of gas voids in the body of the insulation wall.

The most recent and most important improvement in the direction of the suppression of ionization is the so-called oil filled principle in which by the use of oil channels and thin oils, it is aimed to furnish a sufficient supply of oil at all times and at all places to prevent any tendency to the formation of gas voids resulting from temperature variation.

Of the relative value of the 2 classes of effort just described for the increase of the life of cables, there can be no question of the outstanding importance of the second group, and particularly of the oil filled principle. The remarkable improvements in ionization characteristics and the increases in current and voltage ratings of cables of the type *H* and oil filled types on the one hand, and the failure to find refractory materials or preventive measures in the solid type of cables on the other hand, clearly demonstrate the directions in which improved cable performance must be looked for. In this statement it will be understood that we are considering the possibilities offered by underlying physical principles only, and have not introduced consideration of the economic element of relative cost. The relatively lower cost of the solid cable and clear knowledge of its limitations will insure probably for always its wide use in the lower voltage ranges. But for increased current capacities, higher voltages, and higher temperatures, the oil filled cable is indicated clearly and probably will find wider use as its cost is reduced and its ultimate possibilities are explored more completely.

The dominant influence of internal ionization on the life of solid cables has overshadowed the question

Full text of "The Life of Impregnated Paper" (No. 33-72) presented at the A.I.E.E. summer convention, Chicago, Ill., June 26–30, 1933.

of a possible inherent influence of the impregnating oil itself on the life of impregnated paper. As a consequence, this question has received little or no experimental study. Specifications for a cable oil are limited usually to values of low-voltage d-c conductivity, power factor, dielectric strength, aging under temperature as measured by conductivity and power factor, and viscosity as related to the purchasers' or manufacturers' ideas of its bearing upon permanence of impregnation. By sufficient care in refinement, it is possible to meet these specifications with a very wide variety of oils and as a consequence this variety in fact extends itself in considerable measure to the cable oils now in use.

In the oil filled cables so far installed and operated, the oils employed have been limited to only 1 or 2 grades, and there is no knowledge as to the inherent properties which have given them their value, nor has any comparative study been made looking to a determination of important oil characteristics and the relative behavior of the large number of available oils. It is high time, therefore, that studies of this character be begun.

The Materials and Test Samples

This paper reports the results of a series of accelerated life tests on impregnated paper samples in which effort has been made to eliminate all variable factors and conditions except those pertaining to the oil. To this end a single paper has been used, and all test samples assembled, dried, evacuated, and impregnated as nearly as possible under identical conditions. The impregnation program adopted aimed at practically complete impregnation, so that gaseous ionization would be eliminated as an important factor in the life of the samples. This result seems to have been attained as will appear. With gaseous ionization either absent or reduced to very low terms, it is believed that the interesting differences which have been found in the behavior of the various oils are inherent either in the properties of the oils themselves or in the relation of these properties to the structure of the paper.

The Paper. The same grade of wood pulp paper tape as furnished to the cable trade by a well-known manufacturer was used in all the samples. It was not supercalendered and had the following characteristics at 25 deg C:

Thickness	0.004 in. (0.01016 cm)
Width	1 in. (2.54 cm)
Specific gravity	0.937
Gurley air resistance	640 sec
Effective capillary radius	8.2×10^{-6} cm
Conductivity (dry)	9.5×10^{-16} mhos per cu cm

The Oils. Fourteen different oils have been studied, as furnished by 4 manufacturers. Some description of the oils and their principal physical constants are given in Table I. The oils for the most part, are those offered to the cable trade. Exceptions are No. 104 and notably Nos. 109 to 113, these latter having been prepared by a well-known refiner as having special characteristics for these experiments. In connection with most of these oils it has not been possible to secure complete information either as to their origins, their programs of refinement, or their principal chemical characteristics. This applies particularly to those oils which now are sold to the cable trade. As may be seen, most of the oils are those commonly employed for solid core cables. Three, however, Nos. 104, 108, and 113, are thin oils such as used in oil filled cables. The differences in viscosity in these 2 groups are quite wide.

Most of the oils were shipped to us protected by an atmosphere of carbon dioxide or of nitrogen. This condition was maintained by us and at no time before completion of the impregnated sample was the oil exposed to the air. Before admission to the impregnating tank, the oil was sprayed into a vacuum equivalent to one millimeter of mercury, passing down over a series of cones to a heating tank where it was elevated to a temperature of 60 deg under vacuum, and thereafter drawn into the impregnating tank. The d-c conductivity and dielectric strength of the oil was measured both before and after this treatment. A substantial lowering of conductivity and an increase of dielectric strength was found in practically all cases. (See Table I.)

The Impregnated Samples. Each sample consisted of 16 layers of the 0.004-in. paper spiralled in cable fashion with butt joints and with 1/4 width overlap,

Table I—Oil Properties

Oil No.	Base	Pour Point °C	Flash Point °C	Specific Gravity at 40° C	Viscosity Poises at 40° C	Surface Tension Dynes/Cm at 40° C	Penetrative Power $\times 10^{-3}$ (Kraft) at 40° C	Dielectric Strength Volts: Before Treatment	Dielectric Strength Volts: After Treatment	20-Min Conductivity Mhos/Cu Cm $\times 10^{-14}$ at 40° C: Before Treatment	20-Min Conductivity Mhos/Cu Cm $\times 10^{-14}$ at 40° C: After Treatment	P.F. of Imprg. Sample at at 40° C	Life at 400 Volts/Mil (Avg of 20-Mm Sets) in Hours
100	"Undewaxed" paraffin	35.0	274	0.8788	7.5	51.8	5.57	20,175	27,960	105.0	34.2	0.00275	1,118
101	Paraffin	15.7	296	0.881	5.7	31.2	5.0	16,864	25,850	605.0	218 0	0.00353	974
102	Semi-refined naphthene	−7.0	288	0.9268	7.2	20.1	3.55	19,931	29,827	1,630.0	1,313.0	0.00483	2,948
103	Naphthene (phenol extract)	19.3	255	0.96				14,670	25,620	11,900.0	6,400.0	0.00872	20.8
104	Highly refined white oil	0.0		0.83	0.132	32.0	33.0	31,100	31,550	1.4	1.0	0.00264	12,882
105	"Dewaxed" paraffin	−7.0	282	0.8829	4.9	31.3	5.47	17,552	25,500	322.0	84.8	0.00276	1,599
106	75% No. 105, 25% rosin by weight	4.4		0.935	17.5	21.6	2.28	27,660	28,845	130.0	149.0	0.00282	1,096
107	Highly refined paraffin	4.4	263	0.903	4.07	38.3	6.52	27,837	28,820	7.34	5.75	0.00258	1,053
108	Refined light oil	−29.0	149	0.8805	0.1602	28.2	28.2	27,640	26,990	12 6	24 8	0.0027	9,081
109	Highly refined naphthene	−6.7	271	0.9015	2.46	33.0	7.67	18,410	27,790	32.4	22.0	0.00238	7,146
110	Refined naphthene	−7.0	294	0.903	4.82	32.8	5.48	21,600	31,710	47.1	22.8	0.00261	2,568
111	Paraffin blend	−4.0	202	0.8693	0.368	32.9	19.5	27,150	27,763	103.0	74.3	0.00376	6,510
112	Paraffin blend	−2.0	218	0.878	0.878	32.9	12.85	29,400	33,540	7.9	5.4	0.00309	1,929
113	Refined naphthene	−17.8	190	0.891	0.37	30.3	18.96	29,520	30,975	81.7	61.2	0.00289	14,304

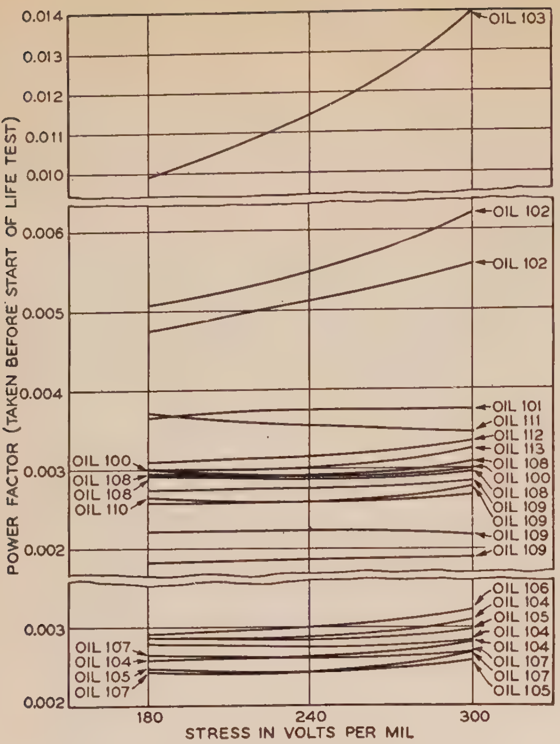

Fig. 1. Power factor-voltage curves

Kraft paper—various oils
Standard construction and treatment
40 deg C

on a 2.5-cm diameter smooth brass tube as high voltage electrode. The outer or measuring electrode (60.96 cm long) was of lead foil reënforced with thin sheet lead. This electrode was protected by guard rings and ends of reënforced insulation. Both high voltage and measuring electrodes were perforated at wide intervals with very small holes to facilitate impregnation. Drying, evacuation, and impregnation were carried out at 2-mm mercury pressure in the standard specimens for life test. After impregnation in the vacuum tank, the specimen was transferred to the high voltage test box containing 3 open oil tanks. The test specimens were made in sets of 3, and 1 specimen was placed in each of the oil boxes and immersed in the oil in which it was impregnated. The oil tanks were themselves deeply immersed in an outer bath of circulating oil permitting temperature adjustment between 25 deg and 80 deg. The whole assemblage of test tanks was enclosed in a large outer wooden box with thermal insulation, through which high voltage porcelain bushings permitted connection of the test specimens to the high voltage source. More detailed descriptions of the test samples as well as of the methods of drying, impregnation, measurement of power factor, temperature, loss, voltage, life, etc., have been given in a foregoing paper.[1]

Measurements, Tests, and Results

The d-c conductivity and the dielectric strength of each oil was measured as received and after the vacuum treatment referred to above. Measurements were also made of the viscosity and surface tension and the penetrative power,[2] or capillary constant, in each case, the results being given in Table I. The power factor and initial or short time conductivity measurements were made on several of the oils, the values for which, and their significance as bearing on dielectric loss in the impregnated sample and other discussion, have been given in a separate paper.[3]

The impregnated specimens were constructed in sets of 3; usually 2 such identical sets were tested for each oil; often there were 3 sets and sometimes more. Before the life test, measurements of power factor, as related to voltage in the range of 180 to 300 volts per mil and at 40 deg C were made on each of the 3 specimens of 1 set. The results of these tests are

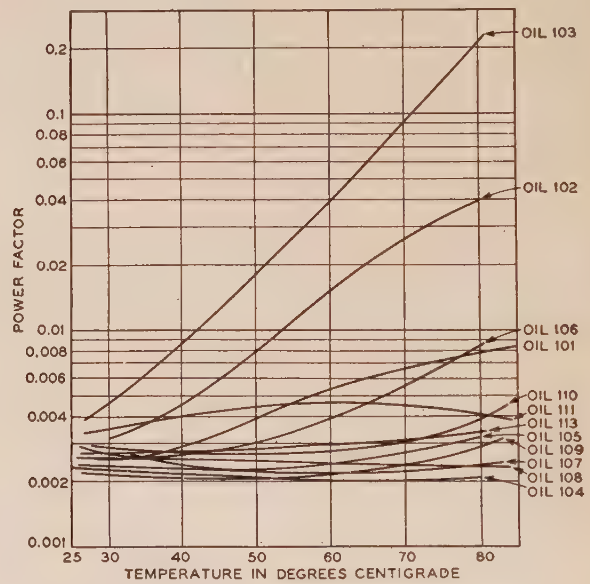

Fig. 2. Power factor-temperature curves

Kraft paper samples impregnated with various oils
Power factor measured at 180 volts per mil

assembled in Fig. 1. Also in each case power factor at 180 volts per mil was measured over the temperature range of 25 to 80 deg C. The results of these tests are given in Fig. 2. Power factor at 180 volts per mil was also read at intervals during the life tests as given in Fig. 3 for the entire series of tests, and in Figs. 4 and 5 for special cases.

In the accelerated life tests (150 in all) each sample was tested singly, being taken one by one from the impregnating chamber within which an atmosphere of nitrogen at atmospheric pressure was maintained. The life test was started at 400 volts per mil, maintained for one hour, then 500 volts per mil for one hour, then 600 volts per mil for 10 hours, 650 volts per mil for 10 hours, 700 volts per mil for 37 hours, 750 volts per mil for 40 hours, 800 volts per mil for 40 hours, 850 volts per mil to failure. These tests were made at 40 deg C, this value being maintained within a fraction of a degree by automatic means.

The results of the life tests on all the oils are summarized in Tables II and III. Table II reports those oils either known to be or believed to be of so-called

1. For references see numbered list at end of paper.

paraffin base, and as furnished by several different refiners; and Table III reports a special group of oils developed for these tests by one refiner and all stated to be of naphthenic base. Exact information as to the origins and differences in processes of refinement has been withheld in all cases. It will be noted from Tables II and III that the complete history of the test as regards the duration of life at each value of stress, together with the total life of each sample, and the average life of the entire group for each oil, are given. Moreover, in the last column the average life per group as reduced to 400 volts per mil by the eighth-power law is also given. As is well known in breakdown tests of this character, there is usually a fairly wide variation in the results as observed on successive similar samples. We have not escaped this difficulty and in the results as reported we have had to use our judgment as to the weight to be attached to life values of individual specimens falling well away from the average value pertaining to the group. As indicative of the results of individual tests we note as of average uniformity set *SS*, oil No. 111 giving 5,706, 6,322, and 5,119 hr respectively at 400 volts per mil. One of the poorer examples as regards spread of results was set *MM*, oil No. 102, giving 4,004, 1,427, and 2,494 hr, respectively, at 400 volts per mil. In the curves and figures as reported, the values are the average values (see Table III) of groups of 3, 6, or 9, as the case may be, with occasional elimination of one apparently abnormal specimen.

The collected results of the life tests, as based upon the average performance of all specimens tested, are shown in Fig. 3 in which the horizontal scale is the actual life in hours and the vertical scale gives the power factor at 180 volts per mil, as measured at intervals during the life run. At the top of the figure successive increments of stress and the duration of each are also given. Each curve refers to a single oil. The dotted sections show the life after the last measurement of power factor. If the values of life are reduced to 400 volts per mil, say by the eighth-power law, the differences among specimens as reported with the various oils are much more pronounced than as indicated in Fig. 3.

A more intimate picture of the change of power factor during the life test is given in Figs. 4 and 5 as taken for single samples. In these the horizontal scale is again linear in actual hours of test. Figure 4 is typical of those specimens having relatively long life with no material change in power factor until the very last stages, within which the rise in power factor is very rapid. In Fig. 5 is shown a slow and uniform rise of power factor throughout a relatively long life followed by a rapid rise in the last stages of the approach to breakdown. In Fig. 5 is also shown the

Table II—Paraffin Oils, Accelerated Life Test History of 2.0-mm Mercury Sets

Oil	Specimen	Number of Hours at: (Volts per Mil) 400	500	600	650	700	750	800	850	Total No. Hours	Avg No. Hours	Avg Life at 400 V/M Hours
	KK-1	1	1	10	3.4					15.4		
100	KK-2	1	1	10	10.0	19.3				41.3	24.4	1,118
	KK-3	1	1	10	4.5					16.5		
	S-1	1	1	10	10.0	5.5				27.5		
101	S-2	1	1	10	10.0	5.6				27.6	23.6	974
	S-3	1	1	10	3.7					15.7		
	H-2	1	1	10	10.0	37.0	40.0	1.5		100.5		
	H-3	1	1	10	10.0	37.0	40.0	30.8		129.8		
104	I-1	1	1	10	10.0	37.0	11.0			70.0	106.1	12,882
	I-2	1	1	10	10.0	37.0	30.7			89.7		
	I-3	1	1	10	10.0	37.0	40.0	40.0	1.5	140.5		
	N-1	1	1	10	10.0	6.6				28.6		
	N-2	1	1	10	9.0					21.0		
105	N-3	1	1	10	10.0	31.2				53.2	31.6	1,599
	P-1	1	1	10	10.0	8.5				30.5		
	P-2	1	1	10	10.0	7.9				29.9		
	P-3	1	1	10	10.0	4.5				26.5		
	CC-3	1	1	10	10.0	4.4				26.4		
107	HH-1	1	1	10	10.0	1.7				23.7	25.7	1,053
	HH-2	1	1	10	10.0	4.0				26.0		
	HH-3	1	1	10	10.0	4.7				26.7		
	EE-1	1	1	10	10.0	37.0	40.0	1.4		100.4		
108	EE-2	1	1	10	10.0	37.0	14.1			73.1	91.6	9,081
	EE-3	1	1	10	10.0	37.0	40.0	2.2		101.2		
	SS-1	1	1	10	10.0	37.0	11.2			70.2		
	SS-2	1	1	10	10.0	37.0	15.3			74.3		
111	SS-3	1	1	10	10.0	37.0	7.3			66.3	75.5	6,510
	TT-2	1	1	10	10.0	37.0	10.0			69.0		
	TT-3	1	1	10	10.0	37.0	38.7			97.7		
	VV-1	1	1	10	10.0	23.0				45.0		
112	VV-2	1	1	10	10.0	8.5				30.5	35.4	1,929
	VV-3	1	1	10	10.0	8.8				30.8		
	XX-1	1	1	10	10.0	21.3				43.3		
105	XX-2	1	1	10	10.0	25.8				47.8	54.8	3,904
(At 70° C)	XX-3	1	1	10	10.0	37.0	14.2			73.2		
	AA-1	1	1	10	10.0	3.9				25.9		
106	AA-2	1	1	10	10.0	10.6				32.6	26.8	1,176
	AA-3	1	1	10	9.9					21.9		

temperature variation in the oil just outside the specimen, upper curve, and that inside the tube forming the high voltage electrode. As a general thing these 2 temperatures were closely the same except in the last stages of life when the losses were increasing rapidly and when the difference would sometimes rise to 4 or 5 deg.

Of the total number of breakdowns observed 97 per cent occurred under the central electrode. A few occurred under the guard electrodes, and 1 or 2 failures under the reënforced ends have not been recorded. The failures for the most part were clean punctures, perhaps a milimeter or more in diameter at the inner and outer electrodes and 5 mm in diameter and often smaller within the insulation wall, usually with some adjacent scorching, dendrites, and gas formation. Conditions throughout the sample after failure generally were uniform longitudinally, although there was often a pronounced variation in the amount of gas formation radially through the thickness of the insulation wall. In general the appearance of the samples after failure was such as to indicate that the deterioration leading to failure was quite uniform over the whole length of the sample. One of the striking features evident on dissection, particularly in the paraffin oil samples, was the presence, practically in every case, of gas, uniformly distributed through 4 or 5 layers and the further fact that the occurrence of this gas was limited to the last stages of life. The amount of this gas was definitely less in the naphthene group. A number of samples of both types of oil were opened after long life and before approach to failure. No gas was ever found in these specimens. Furthermore, a number of specimens were carried to 800 volts per mil, maintained at this stress for a number of hours and then removed without failure. No gas was found in these specimens. No wax has ever been found in any of the specimens. These facts lead us to feel that gaseous ionization in the ordinary acceptance of the term was not present in any of these specimens and that impregnation, in the ordinary sense of the term, that is to say, complete absence of visible gas, was complete.

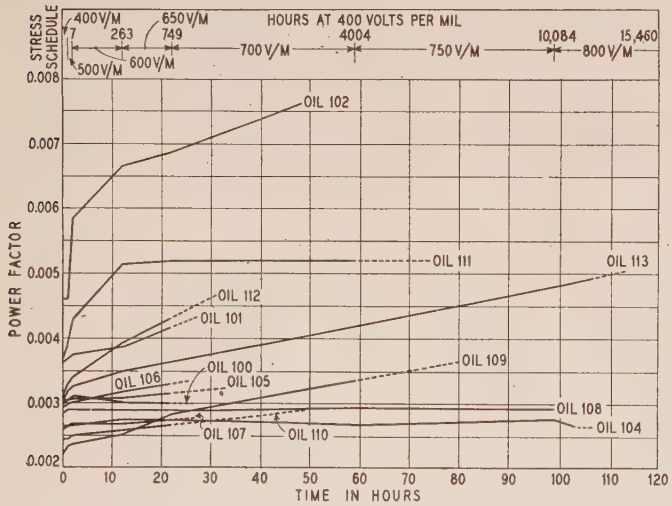

Fig. 3. Power factor-time curves

Representative samples, each oil power factor measured at 180 volts per mil
Life test at 40 deg C

Discussion

Power Factor. The power factor values given in Figs. 1 and 2 indicate a fairly wide variation both in value and type of behavior of the oils. The high values and rising character of the curves for oils No. 102 and No. 103 are in some measure accounted for by the fact that these naphthene base oils were not as thoroughly refined as some of the paraffin base oils submitted to the cable trade by the same manufacturer. Oils Nos. 109, 110, and 113 are more highly refined oils from the same base as No. 102. With this in mind, it may be seen that the variation in power factor values over the whole temperature range studied is relatively small for the entire series of oils. It will be noted also that the variation of power factor with stress is very small over the whole group, up to 300 volts per mil, thus indicating again the absence of gaseous ionization.

Table III—Naphthene Oils, Accelerated Life Test History of 2.0-mm Mercury Sets

Oil	Specimen	Number of Hours at: (Volts per Mil) 400	500	600	650	700	750	800	850	Total No. Hours	Avg No. Hours	Avg Life at 400 V/M Hours
102	V-1	1	1	10	10	37.0	10.8			69.8	45.9	2,947
	V-2	1	1	10	10	21.6				43.6		
	MM-1	1	1	10	10	37.0				59.0		
	MM-2	1	1	10	10	7.7				29.7		
	MM-3	1	1	10	10	19.8				41.8		
	NN-1	1	1	10	10	3.0				25.0		
	NN-2	1	1	10	10	16.5				38.5		
	NN-3	1	1	10	10	37.0	1.0			60.0		
109	OO-2	1	1	10	10	37.0	6.3			65.3	78.5	7,146
	OO-3	1	1	10	10	37.0	17.5			76.5		
	PP-1	1	1	10	10	37.0	40.0	5.2		104.2		
	PP-2	1	1	10	10	37.0	33.7			92.7		
	PP-3	1	1	10	10	32.0				54.0		
110	RR-1	1	1	10	10	26.5				48.5	42.7	2,568
	RR-2	1	1	10	10	5.0				27.0		
	RR-3	1	1	10	10	30.4				52.4		
113	WW-1	1	1	10	10	37.0	40.0	12.3		111.3	113.3	14,304
	WW-2	1	1	10	10	37.0	28.0			87.0		
	WW-3	1	1	10	10	37.0	40.0	42.6		141.6		

The influence of sustained stress on power factor is seen best in Fig. 3. Some of the oils maintain their power factor fairly well up to breakdown (*e. g.*, Nos. 104, 108, and 111) while others (Nos. 109, 113) showed a uniform increase of power factor throughout relatively long lives. There is no relationship apparently between the value of power factor or its rate of increase under increasing stress, and the life of the specimen. In those specimens showing a uniform rise of power factor with increasing stress through life, this relatively slow increase is to be distinguished from the final rapid rise of power factor as failure is approached. The slow increase with stress apparently is an inherent property of the oil involving no instability. The final rapid rise of power factor evidently is the onset of instability and

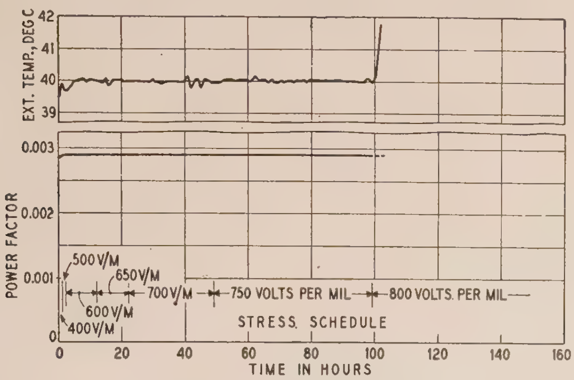

Fig. 4. Power factor-temperature-time curves

Specimen *EE*-3, compound No. 108
Power factor measured at 180 volts per mil
40 deg C

temperature rise in accordance with the thermal theory of breakdown.

Differences in Life. It is evident from Tables II and III and Fig. 3 that there are wide differences in the lives of the various groups of samples, all of which have been impregnated under identical conditions and tested in the same program, the various groups differing only as regards the oil. Looking for an explanation of these differences, it may be noted that for the most part the samples showing the shortest lives are those impregnated with compounds of relatively high viscosity, commonly used in solid cables, as for example, Nos. 100, 101, 105, and 107. In this class also is found oil No. 106 containing 25 per cent of rosin. On the other hand, 2 oils giving exceptionally long lives, Nos. 104 and 108, are both thin light oils of low viscosity. The naphthene base oils seem to fall in a group to themselves. They are characterized by a power factor increasing with increasing stress, but also by relatively long life. In a general way it may be concluded, therefore, that higher viscosities tend to shorten lives and carefully refined thin oils of low viscosity may give exceptionally long lives. Further, an influence of the basic chemical character of the oils is indicated by the divergence of the naphthene group as shown later.

Life-Capillary Properties. In these studies it has been hoped to go much further than a mere experi-

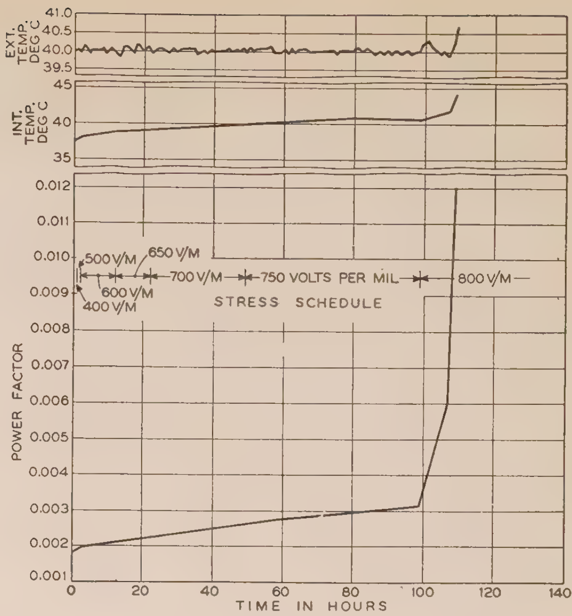

Fig. 5. Power factor-temperature-time curves

Specimen *QQ*-1, compound No. 109
Power factor measured at 180 volts per mil
40 deg C

mental comparison of the lives of paper samples as impregnated with various oils. The chief purpose before us has been to find if possible some relation between the physical or chemical properties of the oils and the lives of samples impregnated with them. We believe that we have found an important relationship of this character in the capillary properties of the oils as related to the paper. We have found, for example, that the rate of rise of each one of these oils in a vertical strip of the paper obeys the well-known law of the rise of a liquid in a small capillary tube. This means that it is possible to assign to each oil a definite value of "penetrative power" K, which is a measure of its power for penetrating the pores of the paper. The penetrative power depends upon the viscosity and the surface tension of the oil, and upon the effective capillary radius of the pores within the paper. The complete expression for K is:

$$K = \left(\frac{r}{2}\right)^{1/2} \cdot \left(\frac{\gamma}{\eta}\right)^{1/2}$$

in which

r = the effective capillary radius of the paper pores
γ = the surface tension in dynes per centimeter
η = viscosity in poises

Over such a group of oils as tested here the variation in surface tension (see Table I) is much less than that of the viscosity and so the latter is by far the more important factor determining the differences in their penetrative powers.

The rise of an oil in a vertical strip of paper is given by the equation $l = K \cdot t^{1/2}$, where K = the penetrative power, l = the height of rise in centimeters, and t = the time in seconds. A complete account of the experiments leading to the determination of the values of K for each oil, its variation with temperature, the effective capillary radii of different papers, and other interesting data on capillary action

have been given in a separate paper.[2] The values of K at 40 deg C for each of the oils studied, as related to the 0.004-in. paper are given in column 8 of Table I. It will be seen that K ranges from 2.28 for the rosin oil mixture, No. 106, up to 33 for the thin white oil, No. 104. The variation of the penetrative power with temperature for each of the oils is shown in Fig. 6.

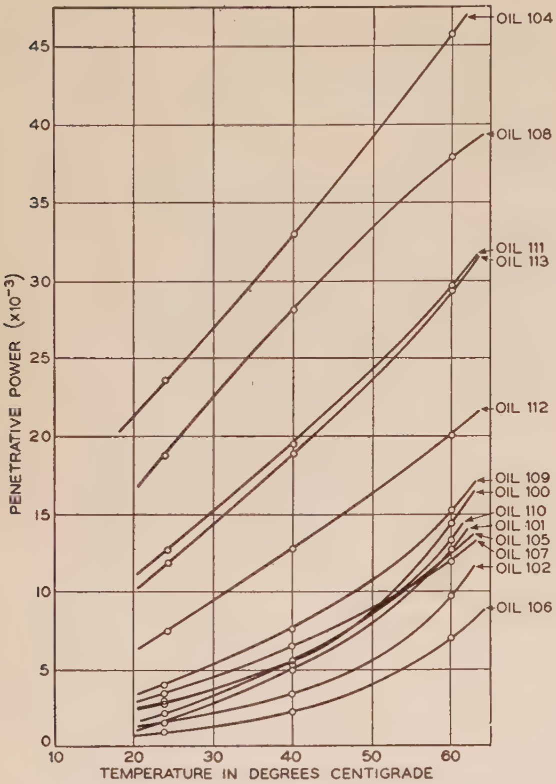

Fig. 6. Penetrative power versus temperature

Various insulating oils
4-mil kraft paper

In Figs. 7 and 8 the average life of the several samples impregnated with each oil has been plotted as related to the penetrative power. In Fig. 7 the abscissas are the values of the overall lives in hours without reference to the values of stress. In Fig. 8 the total life in each case has been reduced to 400 volts per mil by the eight-power law. As seen clearly in these figures, 2 definite lines or curves are indicated connecting in definite relationship the penetrative power with the life of the oil. The oils constituting the lower curve are all of naphthene base. All of the oils on the upper curve except oil No. 108 are known to be of paraffin base. Oil No. 108 is said to be of naphthenic base but is known to have a different origin from the oils constituting the lower curve.

In order to test the interesting relationship indicated here, several auxiliary studies were made. For example, a set of samples was constructed using oil No. 105 in which, however, the temperature of impregnation and test was 70 deg C instead of 40 deg C, thereby lowering the viscosity and increasing the penetrative power markedly. The result was to more than double the life as indicated in Fig. 7. Impregnation at higher temperatures with subsequent life test at 40 deg gave no increase of life. In another case, the viscosity of a well-known paraffin oil (No. 105) was lowered substantially by mixing with ligher oils. The results showed corresponding increases of life as shown by points 111 and 112, Figs. 7 and 8. Similar variations of the viscosity carried out by the refiner on the oils of the naphthene group, for the purpose of both increasing and decreasing their penetrative powers, were reflected immediately in corresponding differences in life.

There appears to be no doubt, therefore, that in gas-free cable insulation there is a definite relationship between the capillary properties of the oil as related to the paper, and the life of the insulation under high stress. The relationship perhaps is not quite so definite as indicated in Figs. 7 and 8 because the spread of the results on each oil is not indicated. If, however, all of the life test results from Tables II and III be included, it still will be found that there is no overlap among the values giving the 2 curves of Figs. 7 and 8, which are based upon the average values for each oil. A linear relationship is suggested in Fig. 7, but this is scarcely possible in view of the continually increasing values of electric stress. On the other hand, the upper parts of the curves in Fig. 8, based on life at 400 volts per mil, also approach fairly closely to a linear relationship. Uncontrollable variations among the specimens and the spread of test results are quite sufficient to account for the differences in the shapes of the 2 curves of Fig. 8.

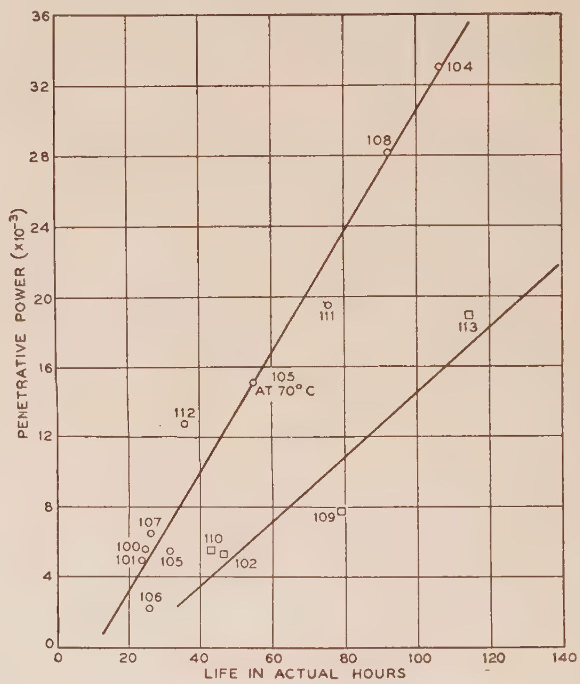

Fig. 7. Penetrative power-life curve

Kraft paper impregnated with various oils at 2.0-mm mercury
Life test at 40 deg C

The 2 separate curves for the paraffin and naphthene groups clearly suggest that the basic chemical structure of the oil also has a bearing on life. This

indication is still further strengthened by the apparent identity of the law connecting penetrative power and life in 2 groups.

It is interesting to speculate on the particular significance of the indication of the importance of capillary penetration. It immediately suggests that failure is removed to longer periods, the more completely the paper fiber is penetrated or saturated with the oil. This picture then immediately suggests as a cause of failure some action such as ionization in the microscopic channels of the cellulose fiber. That this picture is a true one is borne out also by tests made at evacuation pressures of 0.25 mm[1] in which a noticeable increase of life was found. It seems certain, therefore, that the residual air or gas remaining in the paper even below evacuation and impregnation pressures of 1 mm also plays a part in the life history. It is to be noted, however, that these residual traces of air are those existing in microscopic channels only. There is no evidence in these experiments that gaseous ionization in the original acceptance of the term, plays any serious part in the deterioration of these specimens. Gaseous ionization, if involved in the failure, is of a different and much smaller order of magnitude than that occurring in solid cables. Moreover, it is of such a character as to be subject to influence or control by the capillary forces of the oil in its penetration into the paper.

In a recent paper M. Höchstadter and W. Vogel[4] reach the conclusion that breakdown in thoroughly impregnated paper insulation is of pure electric rather than thermo-electric character. The evidence of our experiments is against this view. As indicated above, we find no serious temperature change at high stress over long periods of time, thus far bearing out the conclusions of the authors mentioned. On the other hand, we have clear evidence

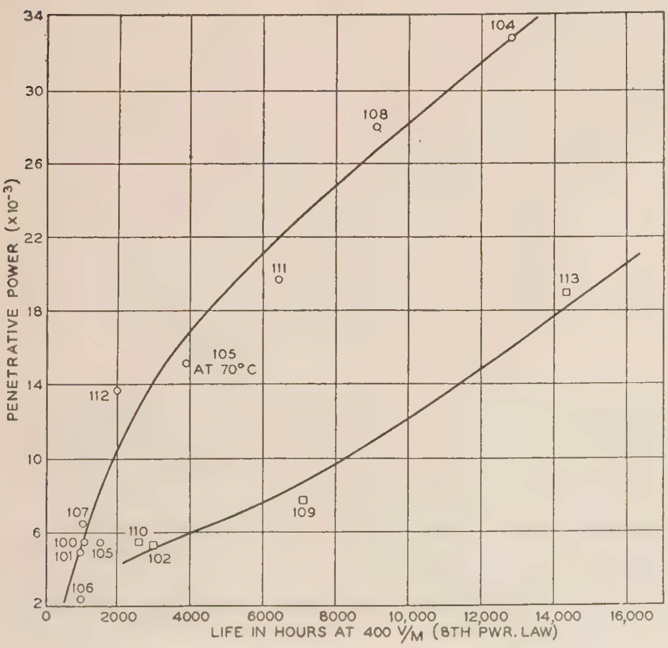

Fig. 8. Penetrative power-life curve

Kraft paper impregnated with various oils at 2.0-mm mercury
Life test at 40 deg C

of approach to breakdown over several hours, during which there is a relatively rapid rise of both temperature and power factor. We conclude, therefore, that while thoroughly impregnated paper insulation may withstand extremely high stress for long periods at constant values of loss and temperature, breakdown, when it comes, is not of pure electric or other sudden type, but has all the characteristics of the so-called thermo-electric failure.

It should be emphasized again, perhaps, that the results reported here pertain to a degree of impregnation and its protection which are quite unattainable under the present methods of manufacture, handling, and operation of high voltage cables. Nevertheless, it has been shown that under controlled conditions impregnated paper can withstand stresses and attain life under stress far in excess of the values pertaining to the present usage of this important type of insulation. It appears a pertinent question whether it is not advisable therefore by modified methods or increased costs to take up some of this difference, not only in the oil filled cables of the upper ranges of voltage, but also possibly in those of solid type for lower voltages.

Conclusions

1. A series of accelerated life tests has been made on one grade of paper as impregnated with 14 different high grade insulating oils. Wide differences in life have been found.

2. The influence of dielectric loss on the life of impregnated paper is within wide limits, negligible as compared with other factors.

3. The values of power factor and their characteristic changes during life tests have no apparent relation to the life of well-impregnated paper.

4. It is shown that the origin or basic chemical structure of the oil has an important bearing on the life of the impregnated paper.

5. Thoroughly impregnated paper will withstand electric stress far in excess of the values of practice over long periods of time without apparent change. Breakdown, when it comes, is of thermo-electric type, the approach to which may extend over several hours.

6. The differences in life in the oils of one base or origin are related directly to the capillary penetrative power of the oil into the paper. Measurements have been made of this capillary constant for each oil. For oils of one type and for a single grade of paper the life of the paper under electric stress is directly proportional approximately to the penetrative power of the oil into the paper.

This work has been carried on under the auspices and with the support of the committee on research of the underground systems committee of the National Electric Light Association, to whom grateful acknowledgment is made. Thanks are also extended to E. W. Greenfield, C. E. Young, and C. O. Newman, research assistants in The Johns Hopkins University, for their skillful and enthusiastic coöperation.

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External Impedance Vs. Short-Circuit Currents

Effects of external impedance on short-circuit currents in synchronous machines and in networks are discussed in this article. The material presented is not claimed to be new; its chief value lies in the confirmation of calculations by test results, which tends to increase confidence in formulas previously developed. The formulas and test data are given in a form convenient for ready reference.

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IN THE CALCULATION of short-circuit currents on synchronous machines or in networks, it is usual practice to treat the circuit as though it consisted of reactance only. The results of such calculations are approximate for several reasons, the 2 factors causing the greatest errors being resistance of the armature circuit and saturation of the machines, both of which usually are neglected. In many cases the consideration of reactance only is justifiable because of its predominant effect over resistance, and also because of the accuracy of the results obtained with the attending greater ease of calculation.

At present, the problem presented by saturation in general is unsolved, but is treated in some cases by the use of arbitrary factors. Resistance, however, has been taken into account in 3-phase short circuits on synchronous machines,[1] but is in need of further treatment in single phase systems.

Questions often arise concerning the manner in which resistance is to be considered in 3-phase short circuit computations for steady state and transient currents, and its effect upon system decrements. Material of such nature is not yet available in text books, but is to be found only in technical literature in relatively recent years.

It is the intent in the present article to give in brief form, the effect of external resistance and reactance in the field and armature circuits. The fundamental equations from which calculations of open- and short-circuit time constants, and transient and steady state currents of a simple 3-phase system may be made are stated, together with a table of additional comparative test data. Further, it is indicated how these equations may be applied to system decrement curves.

Field

The short-circuit characteristics of a synchronous machine depend upon both the field and armature time constants, as shown by Park and Robertson.[2] This is evident also from physical reasoning. The open-circuit time constant of the field circuit normally is given by the relation

$$T'_{do} = \frac{L}{R}\text{ seconds} = \frac{\omega L}{R} = \frac{X}{R}\text{ radians} \tag{1}$$

where L is the total inductance in henries of the field to direct current, and R the total resistance. The time constant, when given in radians, may be converted to seconds by dividing by ω, the angular velocity of the system. The time constant may be expressed also in cycles as the product of its value in seconds and the system frequency.

Usually L and R are taken with reference to the field coils alone, which is quite correct when the open-circuit time constant is obtained through test by short-circuiting the field winding. Under conditions of armature short circuit, however, the field circuit is untouched, and hence L and R are total quantities and are composed of all inductance and resistance in the field circuit.

Usually the exciter armature constants are small in comparison with the field quantities, and hence are neglected; but should the field current be supplied from a constant voltage source and controlled by means of a field rheostat, this external resistance must be taken into account. Additional inductance also may be present, and consequently, the open-circuit time constant of the field is then

$$T'_{do} = \frac{X + X_e}{R + R_e}\text{ radians} \tag{2}$$

where X_e and R_e are the field circuit reactance and resistance external to the field coils themselves.

This open-circuit time constant may be determined either by a test similar to that described in the A.I.E.E. report of the subcommittee on definitions,[3] but with the closed circuit including the external field impedance, or from the rise of field current under sudden application of a direct voltage to the field circuit with the rotor stationary. Auxiliary rotor circuits, of course, are neglected.

Although the definition of T'_{do} is thus stated as in eq 1, perhaps it should be thought of as expressed by eq 2 which is general. For systems of individual excitation, the external field impedance is usually negligible; but for common systems of excitation, or for constant potential sources of field supply, the external impedance is usually present and must be considered in calculations of alternator short circuits.

Armature

Armature currents of a synchronous machine on short circuit, and system currents under conditions

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1. For numbered references see bibliography at end of article.

of fault in a network, are affected by the short-circuit time constant of the field. For the case of negligible armature resistance, the direct-axis transient short-circuit time constant of the field is given by the relation[2]

$$T'_d = \frac{x'_d}{x_d} T'_{do} \text{ seconds} \tag{3}$$

where x'_d is the direct-axis transient reactance of the circuit and x_d is the direct-axis synchronous reactance. Any change in the field resistance hence alters the value of T'_d because of the effect on T'_{do}. Upon inclusion of resistance r in the armature circuit, the time constant used in 3-phase short-circuit calculations of a synchronous machine becomes

$$T'_d = \frac{r^2 + x'_d x_q}{r^2 + x_d x_q} T'_{do} \tag{4}$$

where x_q is the quadrature-axis synchronous reactance of the machine. This expression has been developed by Doherty and Nickle,[1] and is given also by Park.[4] It is an approximation, its accuracy being greater the greater is T'_{do}. For the generator tested, $T'_{do} = 0.70$ sec, the agreement between calculation and test was within 1/4 of one per cent, an accuracy greater than the determination of the machine constants would allow. For a large machine of normal design in which the open-circuit time constant is about 5 sec, eq 4 may be considered exact.

This equation includes the 4 external constants of a synchronous machine which may be varied, i. e., external field resistance and reactance, and external armature resistance and reactance. The first 2 quantities affect T'_{do} as stated by eq 2. The total resistance of the armature and the external circuit is given by r, while any external reactance in the armature circuit is added directly to each of the various machine reactances. In detail

$$T'_d = \frac{(r_a + r_e)^2 + (x'_d + x_e)(x_q + x_e)}{(r_a + r_e)^2 + (x_d + x_e)(x_q + x_e)} \; \frac{X + X_e}{R + R_e} \text{ radians} \tag{5}$$

where the subscript e refers to the external circuits.

Relations for transient and steady state armature currents for 3-phase short circuits on synchronous machines were developed by Doherty and Nickle.[1] Their equations include both resistance and reactance of the external circuits. Knowing the armature flux linkages at the instant of the short circuit, the complete transient wave can be calculated. Considering only the symmetrical value of the alternating component of the short-circuit current, the expression for the effective value of the initial transient current is

$$i' = \frac{e'\sqrt{(r_a + r_e)^2 + (x_q + x_e)^2}}{(r_a + r_e)^2 + (x'_d + x_e)(x_q + x_e)} \tag{6}$$

and for the effective value of the steady state current

$$i = \frac{e'\sqrt{(r_a + r_e)^2 + (x_q + x_e)^2}}{(r_a + r_e)^2 + (x_d + x_e)(x_q + x_e)} \tag{7}$$

where e' is the terminal voltage preceding the short circuit. If x'_d is replaced by the direct-axis subtransient reactance x_d'', eq 6 gives the symmetrical value of the subtransient current at the instant of short circuit.

It is physically evident that the effect of external impedance in the armature circuit is to decrease both i' and i. External field resistance alters neither the initial nor the steady state values; but external field reactance, however, since x'_d is dependent upon it,[6] affects the initial current. Both field quantities influence the intervening current magnitudes. The

Table I—Comparison of Test Data and Calculations

Test No.	Circuit Constants R	r	x_e	T'_d, Seconds Test	Calc.	i', Amperes Test	Calc.	i, Amperes Test	Calc.	Ratio i'/i Test	Calc.
1	1.00	0.07	0	0.156	0.157	94.2	93.6	22.3	21.6	4.22	4.33
2	1.24	0.07	0	0.127	0.126	84.0	83.9	20.0	19.4	4.20	4.33
3	1.87	0.07	0	0.088	0.086	85.6	84.2	19.9	19.5	4.29	4.32
4	1.23	0.49	0	0.258	0.256	39.3	40.6	18.0	18.2	2.18	2.23
5	1.00	0.85	0	0.420	0.448	23.5	23.9	16.0	15.8	1.47	1.52
6	1.87	0.85	0	0.244	0.245	23.3	23.7	15.9	15.7	1.47	1.51
7	1.00	0.45	1.47	0.487	0.483	11.5	11.5	7.9	8.0	1.46	1.44
8	1.23	0.49	0.14	0.278	0.278	35.0	34.5	16.3	16.2	2.15	2.13
9	1.87	0.45	1.47	0.254	0.258	11.5	11 5	7.9	8.0	1.46	1.44

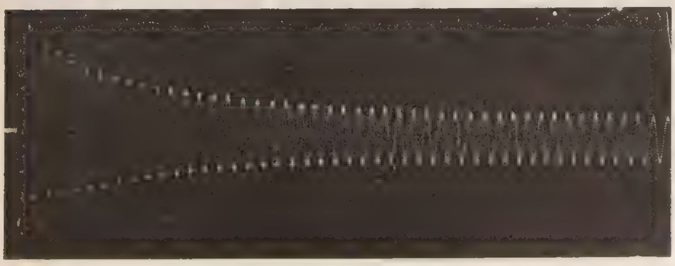

Fig. 1. Oscillogram of short-circuit current corresponding to test No. 1 of Table I. Test ratio of i'/i = 4.22

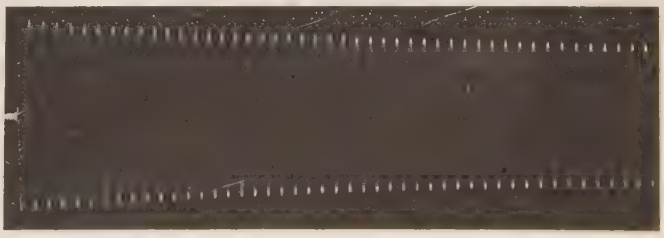

Fig. 2. Oscillogram of short-circuit current corresponding to test No. 5 of Table I. Test ratio of i'/i = 1.47, showing effect of external armature resistance

change in magnitude of the symmetrical component of the short-circuit current is less with greater armature impedance, that is, with increasing values of armature circuit impedance the ratio i'/i decreases, as shown by the oscillograms of Figs. 1 and 2. The upper limit for the ratio is x_d/x'_d, in which case the external impedance is zero and the armature resistance is considered negligible; the lower limit of the ratio approaches unity as the external armature impedance approaches infinity.

Test Results

To illustrate the applicability of the foregoing expressions, Table I gives test and calculated values of short-circuit time constants, and transient and steady-state armature currents on a standard alternator. Also included in the table is the ratio of the symmetrical components of the initial transient and steady-state currents. A 3-phase machine was used for the tests having a rating of 35 kva, 1200 rpm, 60 cycles, 440 volts. The test results were obtained from short circuit at no load and approximately 200 volts. The machine constants are: $x_d = 1.04$, $x_q = 0.565$, $x'_d = 0.234$, and $r_a = 0.07$ in per-unit terms; $R_f = 13.7$ ohms.

Quantities varied were field circuit resistance, and armature circuit resistance and reactance. Respectively these constants are R, r, and x, and, on the basis of normal ohms for field and armature, are total per-unit values for those circuits. To illustrate the accuracy of the relations, the values of the external quantities were varied purposely over fairly wide ranges. The agreement between test and calculations is good, being about 2 per cent in the majority of cases.

Calculation of the short-circuit time constants involved the use of T'_{do}, the open circuit time constant. It was found to be 0.70 sec and was obtained by both of the methods discussed in this article, the results agreeing to within less than 1 per cent. Figures 3 and 4 show oscillograms of both methods.

The equations that have been given for the armature currents and short-circuit time constants of a synchronous machine on 3-phase short circuits apply directly where externally lumped impedances are closed across the armature terminals. Further than this, though, is the application to system decrement curves. Present practice[5] in determining system currents under conditions of fault makes use only of the reactances of the network and of the connected apparatus, and of the short-circuit time constants as affected by the reactance. Calculations and required test data are determined for 3-phase short circuits, but by the method of symmetrical components may be applied to single phase faults.

When the system can be condensed conveniently, it may be treated as a lumped impedance at the terminals of the machine and calculations made as indicated by the relations given in this article. The importance of including resistance lies in both the determination of current magnitudes and the rate of decay during transient conditions because of their bearing on relay settings for circuit breaker operation. For large external armature circuit impedances, resistance considerably affects the transient time constant.

Perhaps it should be pointed out that for a completely offset current wave, in which case the d-c component of armature current is equal in magnitude to the peak of the initial symmetrical component, the resultant effective value of the short-circuit current is given by

$$i_{initial} = \sqrt{i'^2 + (\sqrt{2}\,i')^2} = \sqrt{3}\,i'$$

This is the upper limit for the magnitude of the initial current when it is calculated by using transient reactance; however, the maximum possible current would be found from calculations using subtransient reactance.

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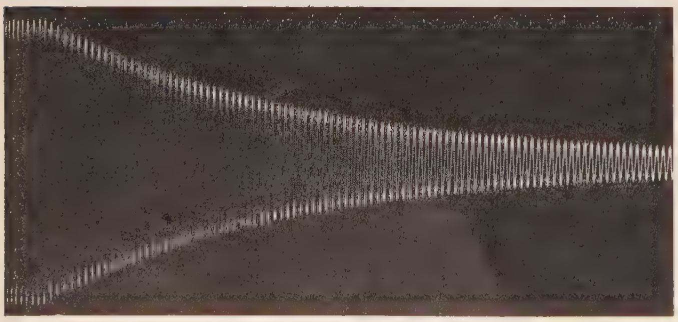

Fig. 3. Decay of armature voltage on open circuit from which open-circuit time constant may be obtained

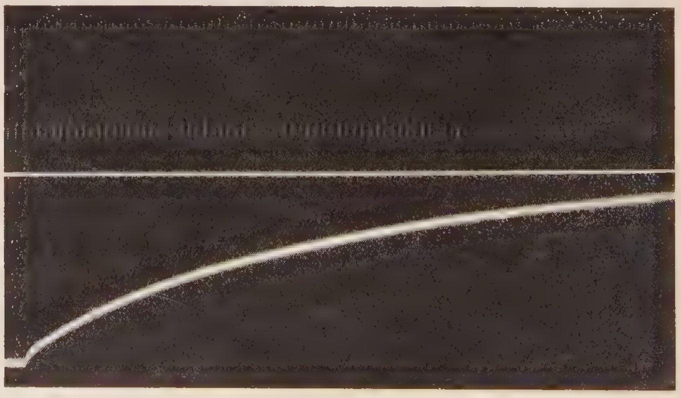

Fig. 4. Field build-up with no external impedance in the field circuit. The open-circuit time constant may be obtained also from this test

Measurement of Wetting of Dielectrics

Penetrability studies have been made to measure the wetting of dielectrics, in an effort to secure information on the electrical characteristics of impregnated fibrous structures. The results of these studies are discussed in this article, which includes studies of the penetration of water, benzene, and several insulating materials.

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THE ELECTRICAL behavior of impregnated fibrous structures is a complex function of the nature and distribution of the constituents. Lowry[1] has pointed out that in many cases calculations of the dielectric constants of solutions and heterogeneous mixtures on the basis of relations which have been proposed do not agree with the experimental facts. It is not surprising to find statements by Riley and Scott[2] and by Wiseman[3] to the effect that it is impractical to discuss dielectric properties of systems of impregnated fibers as functions of the fiber or impregnant alone. It must be expected, rather, that the dielectric properties will in any case depend upon the particular combination of fiber and impregnant, and that in such a combination certain effects may be noted which might not be readily predicted from a study of the constituent materials separately.

Characteristic of such a combination of liquid and solid is the degree of wetting, which aside from its obvious influence during the process of impregnation serves also as a measure of the adhesive forces between the phases. For these reasons it appears fitting to consider methods for arriving at a measure of wetting and to discuss the significance of such measurements. The experimental data obtained so far are preliminary in nature, but they do indicate that the line of attack described here is capable of providing significant data to those interested in impregnated dielectrics.

General

Several investigators, including Whitehead and Hamburger,[4] Roper,[5] and Riley and Scott[2] have stressed the importance of complete impregnation and removal of residual air and moisture. The latter authors correctly state that complete impregnation requires the natural force causing the liquid to penetrate the fine capillary spaces to be high.

This capillary force is a function, not alone of the capillary dimensions of the structure and the properties of the liquid, but also of the specific mutual attraction operative between the solid fiber and liquid impregnant. Thus it will be related to the retention of impregnant in the pores between the fibers, and the displacement of impurities from the fiber surface; probably also to surface conductance and through this indirectly to the dielectric strength, losses, and life of the insulation.

Conduction on cellulose fibers in contact with water has been demonstrated by Stamm[6] and especially Briggs.[7] Murphy and Lowry[8] have discussed the possibility of an electrical conduction in textiles consisting of a movement of ions over fiber surfaces. Riley and Scott,[2] in discussing breakdown of impregnated paper, attach much importance to this type of breakdown.

High adhesion may reduce the conduction by ions on the fiber surface by (1) the impregnant being held firmly to the outer surfaces of the fiber and thus decreasing the solid gas leakage paths, (2) the increase in viscosity of the interfacial phase by high adhesive forces, and (3) the displacement of ionic impurities from the surface owing to high attraction between cellulose and impregnant.

The wetting of cellulose may determine to some extent the effectiveness of a wax impregnant in sealing the fibers from moisture, since good wetting minimizes the possibility that cracks formed on cooling will follow the interface.

In the process of impregnation, the force promoting wetting is measured as the product of the surface tension of the liquid and the cosine of the contact angle liquid-solid. With contact angles other than zero, this corresponds to the Freundlich "adhesion tension" which Bartell and Osterhof[9] have accepted as a measure of the degree of wetting. This product, $\lambda \cos \theta$ (where λ is the surface tension of the liquid and θ the contact angle solid-liquid), will be referred to here, as the "penetration tension" γ thus recognizing (1) that where the contact angle is zero this product may be smaller than the adhesion tension, and (2) that the contact angle may vary depending upon the direction of movement of the liquid-solid-air boundary line over the solid surface. In restricting ourselves to consideration of penetration tension we will be interested in the movement in the direction of the unwetted solid, as occurs in impregnation.

Experimental Attack—Qualitative

If the penetration of 2 liquids of equal viscosity and density into identical paper strips held vertically is observed, it is obvious that the liquid having the higher value of penetration tension will penetrate the farther in a given time. If, on the other hand, a single liquid is employed with strips of dissimilar

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1. For all numbered references, see list at end of article

paper, the liquid will rise in a given time to different heights, dependent upon the capillary structure of the paper, and upon the value of penetration tension peculiar to the combination of liquid and fiber. This latter procedure forms the basis for many

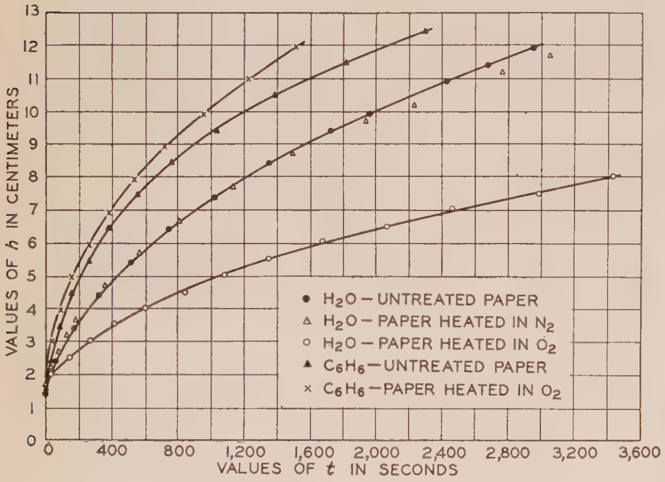

Fig. 1. The effect of treatment of paper upon penetration of water and benzene

current tests of "capillarity." What is often overlooked, however, is that a group of paper samples may fall in entirely different order as regards capillarity depending upon the liquid used.

That this is true has been demonstrated by treating paper to change the surface of the fiber so as to inhibit the penetration of water while leaving the penetration of benzene unaffected. Filter paper was chosen for all tests as representing a pure form of cellulose suitable for a fundamental study of this sort. Experiments are in progress now, however, in which papers employed commercially in dielectrics are being used.

Strips of filter paper 0.5 in. wide were marked lightly with a pencil at each half-centimeter of length. The rise of liquid when one end was suspended below the liquid surface was observed as a function of time. These tests were carried out in a narrow glass tube closed except for a small capillary opening in order to minimize any effect of evaporation. Alternate strips from a particular sheet were exposed to an atmosphere of dry oxygen for 3 days at 130 deg C after which they were tested for penetration with water and benzene and the results compared with those obtained using the original strips.

In Fig. 1 is illustrated the large decrease in the rate of penetration of water caused by the oxygen treatment, an inhibition not shared by benzene, which it may be noted is more akin to the impregnating compounds normally used than is water.

That the change brought about in the paper is not due to heat alone is shown by the fact that heating in nitrogen produces no change in the penetration of either liquid. That it is not due to absorption of grease to which the paper might accidentally have been exposed and which might retard the water is shown by the fact that extraction with benzene does not increase the water penetration. The paper can in some degree be revivified with respect to water penetration by extraction with water.

The explanation must be found in some change in the surface of the cellulose fibers which increases the contact angle water-cellulose without changing the contact angle benzene-cellulose. Recent experiments have shown that similar effects are noted

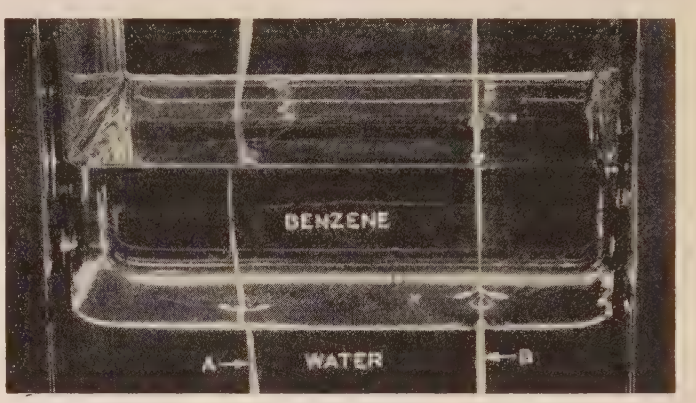

Fig. 2. The effect of oxygen treatment upon the attraction of cellulose for water and for benzene

A. Strip heated in oxygen
B. Untreated strip

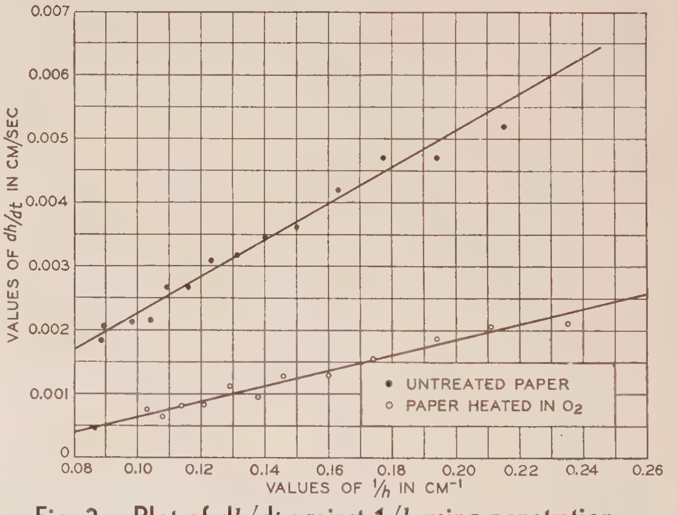

Fig. 3. Plot of dh/dt against 1/h using penetration data of Fig. 1

when paper is subjected to much less severe treatments than that described here.

That we are dealing here with actual attractive forces between the solid and the liquid is demonstrated convincingly by Fig. 2. An untreated strip and an oxygen-treated strip are shown suspended through a benzene-water interface. For the former the attraction of the fiber for the water is greater than for benzene and hence the interface around the strip is drawn up above the general level of the interface, while for the treated strip, exactly the reverse is true; i. e., the attraction for water is less than for benzene and the interface is drawn downward.

Experimental Attack—Quantitative

An analysis of penetrability data such as given in the preceding paragraphs may occasionally give all desired information. However, in general it is desired to relate the rate of rise to the capillary forces exerted and hence to the penetration tension of different liquids, for which something of the effect of viscosity in resisting the movement must be known.

For a uniform capillary tube the rise of liquid is represented by the equation:

$$\frac{dh}{dt} = \frac{R\gamma}{4\eta h} - \frac{R^2dg}{8\eta}$$

where h is the height of rise in time t; R is the radius of the tube; γ the penetration tension; g the acceleration due to gravity; and η and d the viscosity and density, respectively, of the liquid.

Where a structure such as paper is dealt with, this equation cannot be expected to hold owing to the complexity of the capillary arrangement. In another paper, however, Peek and McLean[10] have developed a very similar equation for penetration into a disperse system, as follows.

$$\frac{dh}{dt} = \frac{A\gamma}{4\eta h} - \frac{Bdg}{8\eta} \quad \text{(see footnote*)}$$

A and B are constants determined by the pore size distribution function. B will be equal to A^2 only for the case of uniform pores. Using a given fibrous structure and different liquids, straight lines should be obtained for plots of $\frac{dh}{dt}$ against $\frac{1}{h}$. The slopes m of such lines would be proportional to $\frac{\gamma}{\eta}$ and the intercepts to $\frac{d}{\eta}$. The paper[10] just cited gives results on the penetration of several pure liquids into filter paper confirming the equation developed. Certain limitations of the methods and precautions which must be observed in the experimental set-up are given which will not be treated here.

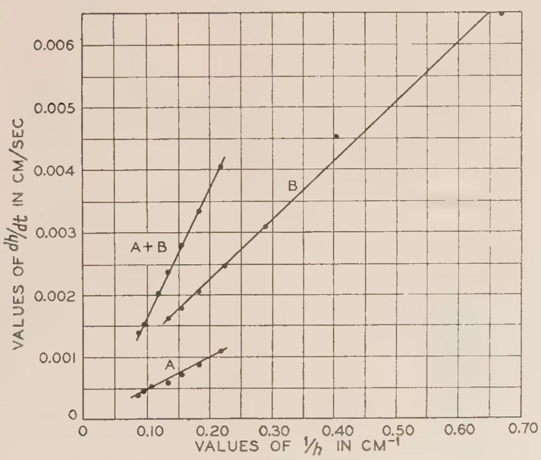

Fig. 4. Penetration of wax A, wax B, and 90 per cent wax B + 10 per cent wax A into paper strips

In Fig. 3 is shown the analysis applied to the data of Fig. 1 on the penetration of water into untreated and oxygen-treated paper strips. Straight lines are obtained, the slopes having values of 0.0288 and 0.0120, respectively, so that it can be stated that the penetration tension has been decreased 58 per cent by oxidation of the cellulose.

If the data on penetration of benzene are attacked in the same way, the slope of the line being designated as m, the following are obtained:

Untreated, $m = 0.0728$
Oxidized, $m = 0.0768$

Since the former run was made at 27 deg C and the latter at 31 deg C it is necessary to multiply the slopes by the viscosity of benzene at these temperatures, which shows that there is no significant change in the penetration tension.

Untreated, $m\eta = 0.0427$
Oxidized, $m\eta = 0.0426$

Results on Impregnating Materials

Results obtained with several insulating materials at elevated temperatures are shown in Figs. 4 and 5. All results are referred to the value of $m\eta$ for benzene. In Table I the values of penetration tension, relative to that of the benzene, are designated as γ' and were calculated as follows for a given liquid, X:

$$\gamma'(X) = \frac{m\eta\,(X)}{m\eta\,(\text{benzene})}$$

The varying values of $m\eta$ for benzene are due to the fact that paper of the same porosity was not used in all of the tests. These data show that for

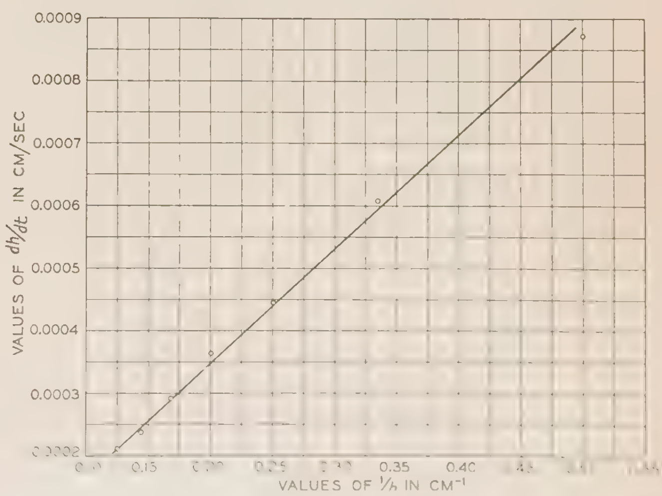

Fig. 5. Penetration of liquid C into paper strips

* Obviously if the average pore size is small and the heights of rise studied small, the second term representing the hydrostatic head becomes negligible and the equation integrates to give $h^2 = \frac{A\gamma t}{2\eta h}$ (for $t = 0$ when $h = 0$). In this event a plot of h^2 against t should give a straight line with a slope proportional to $\frac{\gamma}{\eta}$. Our results on filter paper strips have in general shown a small but significant negative intercept on the $\frac{dh}{dt}$ axis when $\frac{dh}{dt}$ is plotted against $\frac{1}{h}$ showing that while the effect of hydrostatic head is small, it is not entirely insignificant.

these particular materials the ratios of the penetration tensions to that for benzene are in the neighborhood of unity. The value for liquid *C*, a chlorinated hydrocarbon, is significantly higher than for the waxes. The value for the wax *A*-wax *B* mixture falls, as might be expected, between those for the constituents.

Table I—Calculation of Penetration Tension

Fig.	Material*	Temp. °C	η Poises	m	$m\eta$ (Benzene)	γ'
4	Wax *A*	106	0.0800	0.00506	0.000427	0.95
4	Wax *B*	120	0.0265	0.00964	0.000247	.02
4	Wax *B* + 10% Wax *A*	125	0.0260	0.0200	0.000536	0.97
5	Liquid *C*	105	0.0255	0.00197	0.000427	1.17

* All of these materials are commercial products. Wax *A* is a hydrocarbon wax, was *B* a chlorinated naphthalene, and liquid *C* a chlorinated diphenyl.

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Locating Grounds by Distribution Ratio Method

A method of locating ground faults on electric power transmission lines has been developed wherein the location of a fault can be determined accurately and conveniently from the percentage distribution of ground current fed into the fault from the 2 ends of the line. This method has been applied to the Pennsylvania-New Jersey 220-kv interconnection since 1930; results obtained indicate a large saving in time and expense over what normally would be involved in locating the faults by previous methods.

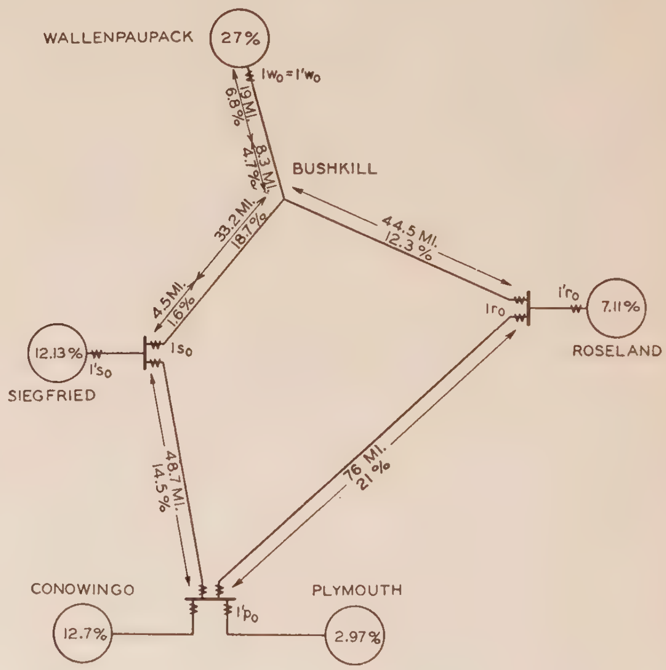

Fig. 1. Zero sequence reactance diagram of Pennsylvania-New Jersey 220-kv interconnection; 100,000-kva base

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PRIOR TO 1930 the 2 methods used for locating ground faults on the Pennsylvania-New Jersey 220-kv interconnection employed (1) fault current-distance curves and (2) distance measurements in ohms by several types of impedance or reactance relays. Because of varying changes in generating capacity and fault impedance during fault conditions, certain errors are inherent in both of these methods. During subsequent study of the problem, it became evident that the zero sequence system constants seldom were affected by switching operations. It was obvious also that the ground currents fed from the ends of any line were functions of the fault distance from the line terminals, and that the ratio of these currents is unaffected by the

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impedance of the fault. From these facts it was deduced that if ground current distribution ratios could be used for locating faults, the discrepancies inherent in methods previously used would be eliminated. This led to the development of the distribution ratio method which subsequently has been used successfully for more than 2 years.

This method employs curves of ground current distribution showing the ground current fed from one end of the line in per cent of total, plotted against line miles to the fault. Since only zero sequence reactance affects the distribution of ground current, an extensive knowledge of symmetrical components is unnecessary. Curves using per cent of total current fed from the ends of the line employ line residual currents. Curves using per cent of part total employ residual currents fed from grounded transformers. Either may be used depending upon which can be recorded with the greater accuracy and economy. A single current element when connected to record transformer residual current will suffice in locating faults on any number of lines radiating from that transformer. Similarly, a single current element is required on the grounding bank at the far ends of these lines.

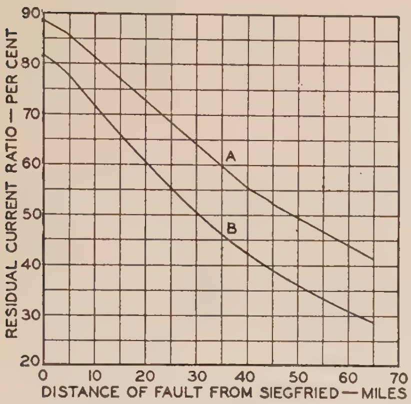

Fig. 2. Curves for locating faults on Siegfried - Wallenpaupack 220-kv line by the distribution ratio method during 1931

Curve A. Ratio of $\dfrac{\text{Siegfried}}{\text{Siegfried} + \text{Wallenpaupack}}$ line residual currents

Curve B. Ratio of $\dfrac{\text{Siegfried}}{\text{Siegfried} + \text{Wallenpaupack}}$ transformer residual currents

Calculations

There are 3 methods of obtaining fault location curves for the distribution ratio method; they are:

1. Calculation when zero sequence reactance values are available.
2. Staged tests at 2 or more locations on a line.
3. Chance recording of ground current at each end of the line for faults at several locations.

For method 1 only the grounding transformer zero sequence reactance values and the physical characteristics of the line need be known. The division of ground current is the inverse ratio of zero sequence reactances. Methods 2 and 3 eliminate errors due to current transformers, instrument calibration, and the zero sequence reactances used in calculations.

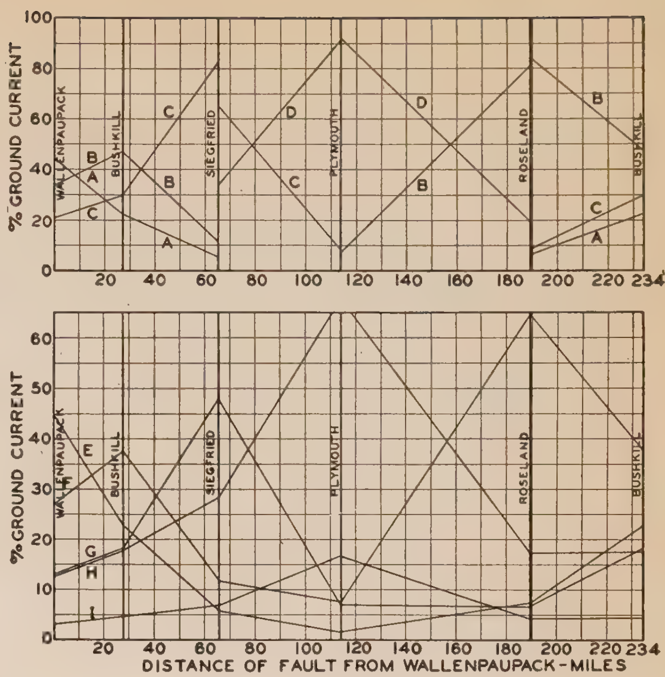

Fig. 3. Curves for locating ground faults by the distribution ratio method on the Pennsylvania-New Jersey 220-kv interconnection

Upper curves show the division of total ground current between the ends of the faulted line; lower curves show this distribution between the 5 stations with grounding transformers

Curves	Per Cent Current From
A and E	Wallenpaupack
B and F	Roseland
C and G	Siegfried
D and H	Plymouth
I	Conowingo

Where the line is of uniform construction and is not affected by adjacent parallel lines, the per cent residual fed from either end is a straight line function. Consequently a straight line may be drawn through any 2 points determined by faults at different and known locations.

A sample application of line residual currents to the location of a fault follows:

Siegfried-Wallenpaupack residual at Siegfried = 1,580 amp
Siegfried-Wallenpaupack residual at Wallenpaupack = 400 amp

$$\frac{\text{Siegfried residual}}{\text{Siegfried} + \text{Wallenpaupack residual}} = \frac{1{,}580}{1{,}980} = 79.7 \text{ per cent}$$

This value when applied to curve A, Fig. 2, indicates the fault location as 12 miles from Siegfried. The actual location was 12.3 miles.

In a similar manner transformer residual currents are applied to curve B, Fig. 2.

Automatic Recording Instruments

Three types of recording instruments have been applied to fault location on the Pennsylvania Power and Light Company system; they are:

1. Graphic high speed ammeters.
2. Oscillographs.
3. High speed photographic recorders.

The only limitation preventing the exact locating of faults is the accuracy of current measurements.

Table I—Fault Location Data for Wallenpaupack-Siegfried Line, 1931

Trip-out No.	Transformer Residual, Amperes: By Ammeters $I''w_0$	By Ammeters $I''s_0$	By Oscillographs $I'w_0$	By Oscillographs $I's_0$	Line Residual Amperes by Oscillographs Iw_0	Is_0	Current Ratios: Transformer Residuals $I''s_0/I''t_0$	$I's_0/I't_0$	Line Residual Is_0/It_0	Fault Distance Miles From Siegfried: Calculated By $I''s_0/I''t_0$	By $I's_0/I't_0$	By Is_0/It_0	Actual by Flashover Indicators
1*	150	1,200				2,880	0.890			0			0
2	375		390	1,655	390	2,080		0.811	0.842		1.0	6.7	6.6
3	594	700	630	730	630		0.540	0.537		26.5	26.9		30.2
4	495	1,056		1,055		1,230	0.682			13.3			16.5
5	414		400	1,200	400	1,855		0.750	0.823		7.4	9.0	7.5
6	354	500	520	885	520	1,310	0.586	0.630	0.716	22.3	17.8	21.3	20.8
7	685	550	720	592	720	907	0.445	0.444	0.561	37.0	37.1	39.5	39.7
8	542	624		657			0.535			27.0			37.8
9	369	870	500	657	500	1,875	0.703	0.568	0.790	11.0	23.7	12.0	9.3
10	306	672	399	600	399	1,580	0.687	0.600	0.797	12.5	20.7	12.0	12.3
11	512	768		770		968	0.600			20.7			27.3
12	548	600	584	795	584	1,050	0.526	0.576	0.642	29.0	23.0	31.0	26.5
13	548			738		937							29.3
14		1,320	315	1,396	315	1,937		0.816	0.860		0.3	4.8	5.3
15	433	1,320	400		400	1,597	0.735		0.800	8.5		11.4	9.2
16**	783		890	552	890	350		0.383	0.282		46.0	65.0	65.0** & 38.0
17	613	552		982		783	0.473			32.5			29.5
18	450	490	670	844	670	814	0.520	0.557	0.548	28.5	24.9	41.3	36.0
19	426	864	624	1,039	624	855	0.670	0.625	0.574	14.2	18.3	37.7	26.5
20	468	1,032	480	1,218	480	1,442	0.687	0.717	0.750	13.0	10.0	17.5	15.7
21†													
22			400		400	400			0.500			49.0	45.0

*Tripout No. 1 developed after several cycles from a two phase into a solid three phase fault.
**Tripout No. 16 was double fault to ground.
†Tripout No. 21 was due to control trouble at Siegfried.
Iw_0, Is_0, etc., refer to the diagram shown in Fig. 1; It_0 represents the total residual amperes or the summation of all ground currents.

For this reason too much emphasis cannot be placed upon the type of instruments used and the care taken in their maintenance. Graphic high speed ammeters should be properly and identically damped at all locations.

Some knowledge of oil circuit breaker performance is essential in order that high speed records of current may be applied properly to fault location. Any single fault location curve is applicable only so long as the system set-up exists for which the curve was determined. Therefore, it is imperative that current values used in fault location be taken at the same time from the start of the fault and prior to switching operations which change the distribution of ground current. The use of high speed oil circuit breakers requires quick initiation and recording by the current instruments.

Application to 220-Kv Pennsylvania-New Jersey Interconnection

Figure 1 shows the line and equipment zero sequence reactances for this interconnection. These values are for the maximum connected capacity. Residual current measurements are made at points indicated by current transformers.

That section of the interconnection between Bushkill and Roseland was not in service until December 1931. Curves shown in Fig. 2 were calculated for this condition, and hence applied to the Siegfried-Wallenpaupack line only. Curves shown in Fig. 3 were calculated for the completed interconnection, and are applicable to fault location at any point around the loop. Ratios obtained from any 2 current records permit fault location; the large number of possible combinations of records thus enables faults to be located even though some of the records may be lost. Current values from stations adjacent to the fault are larger and lead to greater accuracy.

Table II—Fault Location Data, Siegfried-Roseland-Wallenpaupack Tap Line, 1932

Tripout No.	Calculated Miles From Siegfried by the Ratios $\frac{Is_0}{Is_0 + Iw_0}$	$\frac{Is_0}{It_0}$	Actual Miles From Siegfried	Number Phases Faulted to Ground
1			0	1
2	7.0		6.7	1
3	33.7		37.4	1
4			14.5	1
5	32.4	30.7	30.0	1
6	38.0	34.5	38.8	1
7*			65.0* & 34.5	1
8	26.0	33.7	22.7	1
9*	61.6	57.5	65.0*	1
10	57.0	47.5	57.8	1
11			12.0	3
12	65.0	63.0	65.0	1
13	65.0	63.0	65.0	2
14	65.0	64.0	65.0	2
15		81.2	81.2	1
16		81.2	81.2	2
17	37.0	35.0	37.7	1
18	41.0	35.0	37.7	2
19	0	0	0	1

Faults 1 to 11 were caused by lightning, and 12 to 19 were staged tests.
*Tripouts 7 and 9 were caused by double faults to ground.
Is_0 and Iw_0 refer to Fig. 1; It_0 is total residual current.

During 1931 and 1932, 43 faults occurred on the interconnection, 33 of which were on Siegfried-Roseland-Wallenpaupack tap line. Part of this line, 41.5 miles, is not protected by overhead ground wires; 32 of the 33 faults occurred on this unprotected section. Actual fault locations on the Siegfried-Wallenpaupack section were indicated to line patrolmen by line flashover indicators and confirmed by lightning stroke recorder records. During 1933, of the 17 faults that have occurred to date, 13 have been located by this method within a distance of about 2 miles.

Table I shows current values with calculated and actual location of faults which occurred during 1931.

Table II shows only calculated and actual distances from Siegfried for faults which occurred during 1932.

Conclusions

Experience so far with the distribution ratio method has led to the following conclusions:

1. The immediate availability of graphic high speed ammeter records and their close agreement with the oscillograph renders the method of great value for quickly locating and clearing a permanent failure of line insulation. The simplicity of using ammeter records facilitates the station chief operators in approximating fault locations and intelligently directing line patrols.

2. This method provides for a possible economy estimated to be 80 per cent of the cost of line patrolling.

3. It is applicable to any type of fault resulting in ground current whether it be single phase, 2-phase or unbalanced 3-phase.

4. It is not applicable to simultaneous faults at different locations.

Protective Relays on Pa. Locomotives

No current rupturing device is provided between pantograph and main transformer on electric locomotives recently placed in operation on the Pennsylvania Railroad; instead a "pantograph relay" is used which is connected so as to utilize the substation circuit breakers to open high voltage short circuits, grounds, or overloads on the locomotive. A voltage relay is used to change the field strength of the traction motors at a predetermined speed, and slip relays provide protection against wheel slippage.

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PROTECTION of a-c locomotives against electrical faults never has been standardized nor has any system been applied in which one or more groups of engineers have not believed that objectionable or questionable features were involved. Engineers of the Pennsylvania Railroad, in common with many others, do not favor oil switches on locomotives; accordingly, they have developed a system in which locomotive faults ground the trolley wire, thus short circuiting the faulty locomotive and throwing the duty of clearing the resulting current on the substation circuit breakers. This system brought forth the development of an interesting relay known as the pantograph relay, though its functions are not confined to, nor primarily concerned with, the pantographs.

Modern a-c series motors such as those used on the new Pennsylvania locomotives are operated at low magnetic flux to minimize commutation troubles; during the starting period the exciting fields are weakened further by the use of inductive shunts. A newly developed voltage relay makes possible the proper selection between weak and full fields. The high peripheral speeds of these motors make it advisable to protect against wheel slippage, particularly at the higher operating speeds; special slip relays, therefore, have been developed for this purpose. Operation and characteristics of these 3 relays as applied to the type *P5A* heavy duty passenger locomotive are described in this article.

Voltage Relay

The voltage relay is used to change the field strength of the traction motors from weak to full at a proper speed, in this case approximately 15 mph. It has been found that armature voltage gives a sufficiently accurate indication of speed, and that a shaded-pole induction motor operated on voltage may be the actuating element. The requirements are:

1. An operating element to function at the desired speed.

2. Means to prevent the increase in tractive effort, when changing to full field, causing wheel slippage or the tripping of the overload relays.

3. Means to prevent burning out the a-c element at high speeds, when the voltage is approximately 6 times that at pick-up.

4. Provision for the relay to drop out again if the locomotive is slowed down below a desirable full-field operating speed.

5. Provision against a weak field when power is turned on after coasting at high speeds.

6. A high inherent drop-out point, since the voltage on full field at the speed of operation is some 40 per cent greater than at the same speed on weak field.

Essential connections of the voltage relay are shown in Fig. 1. Contact *A* lights a warning lamp just before changeover takes place, so that the engineman will not move the controller and superpose a normal notch on the increment caused by the changeover. Contact *C* makes the changeover and the warning light is put out by an interlock on one of the switches. Contact *B* energizes a locking coil which holds the relay and also opens contact *D*, removing the a-c voltage.

Weak field cannot be obtained on any forward or backward movement of the controller above notch 6. If the controller is shifted to a lower notch, the locking coil is deënergized, reclosing contact *D* before changeover to weak field can take place. This returns control of the field strength to the operating relay element. The actual drop-out of the relay is properly commutated by the auxiliary coil and contact *E* which controls a drop-out resistor.

The locomotive thus is controlled fairly accurately

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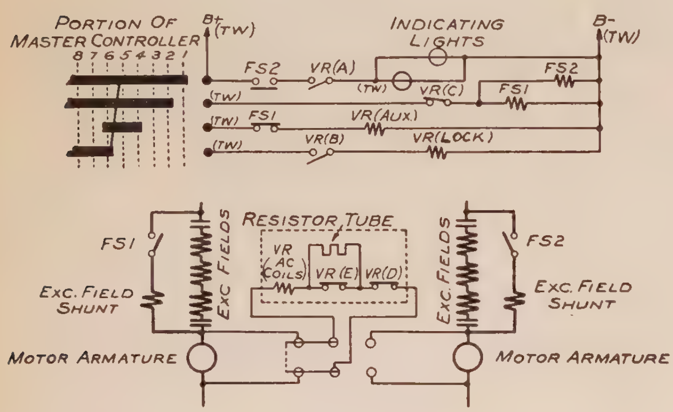
to operate at all times with weak field below, and full field above, a predetermined speed.

Slip Relays

The slip relays, one in each motor circuit, are operated by the same type of motor elements as the voltage relays. They obtain their indication for operation from the differential in voltage between 2 motors connected in series, when one slips or the 2 slip at different speeds.

Figure 2 shows part of one motor circuit, an auto-transformer being connected across 2 traction motors on different axles. The coils of the slip relays are connected between the midpoint of the pairs of motors and the midpoint of the auto-transformer. Except for a certain variation because of regulation, the midpoint of the auto-transformer is always at a potential half way between the points to which its end leads are connected. So long as neither motor is slipping, the voltage at their midpoint is the same and there is no voltage across the slip relay.



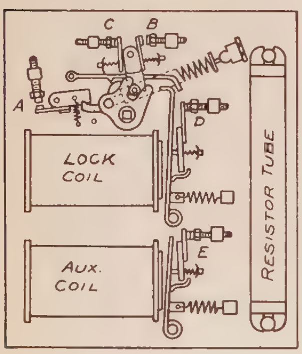


Fig. 1. Voltage relay for changing from weak to full field, and connections

B+ positive lead
B− negative return
FS1, FS2 interpole shunt switch
(TW) train wire
VR voltage relay

Sometimes the 2 motors are not identical, or tire diameters cause them to divide the total voltage unequally. To compensate for such differences, adjusting taps are provided on the auto-transformer; by means of these the slip relay may be so connected that, with neither motor slipping, practically no current will flow through the operating coils of the slip relay.

The voltage balance between the 2 motors is disturbed as soon as one motor slips; as the voltage at the midpoint of the auto-transformer changes only slightly, voltage appears across, and current flows through, the slip relay, starting at a low value and increasing as the differential in speed between the 2 motors increases.

At a nominal differential speed of 5 mph, sufficient current passes through the slip relay to cause it to start to rotate, and to close a contact which actuates a buzzer and an indicating lamp in front of the engineer who then shifts the controller to a lower speed notch. If he can stop the slipping by this means, the relay will return to its original position and the acceleration will continue; should he be unable to stop the slipping or should he take no action, the relay will remain energized and when a nominal differential in speed of 20 mph is reached a second set of contacts open and latch, removing power from the traction motors. It is then necessary for the engineer to turn the controller fully off before he is able to reset the relay by means of the reset switch at his operating position.

Pantograph Relay

The pantograph relay (Fig. 3) is designed to take care of faults that might develop on the locomotive and cause heavy overloads in the transformer primary, and grounds in the primary or in any of the circuits connected to the secondary. Short circuits in the secondary, except where protected by fuses or the motor-overload relays, must go to ground before they are removed, unless they cause a primary overload sufficient to trip the pantograph relay. Any heavy short circuit, however, will go to ground in a brief time.

The primary function of the pantograph relay, called the *PR* relay, is to operate the grounding switch that grounds the trolley thereby shunting the resulting current around the locomotive and causing the feeder breakers in the substation to open. This method effectively protects the locomotive, but is a decided disadvantage to the rest of the system. One of the functions of the *PR* relay, therefore, is to prevent closing this grounding switch if the fault can possibly be cleared by the apparatus on the locomotive. The relay also must be highly sensitive, and yet not trip on surges caused by energizing the main transformer, by sleet, section breaks, etc. A further function, from which it gets its name, is to lower the pantographs after the fault is cleared and thus permit the feeder breakers to reclose. This latter is necessary only when the locomotive apparatus is unable to clear the fault. As the trolley wire is very low in some places, particularly in the tunnel under the Hudson River, it is further necessary to

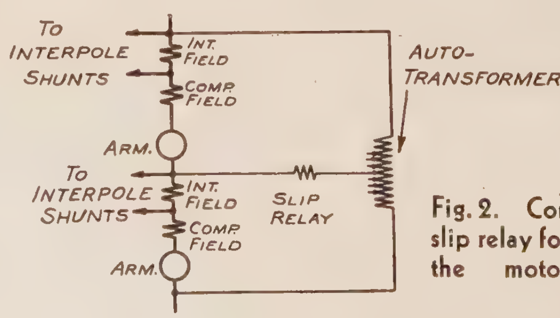


Fig. 2. Connections of slip relay for protecting the motors against wheel slip

prevent lowering the pantographs unless and until the feeder breakers actually do open.

Faults in the main transformer or the bus bar immediately connected thereto cannot be cleared by the locomotive apparatus; hence, when faults of this nature occur the *PR* relay must operate the ground switch. Faults anywhere in the main motor circuits may be cleared by opening the line switches.

The relay consists of a motor element similar to the voltage and slip relays, but with a 2-circuit coil arrangement. One section acts as an overload coil in series with 2 current transformers, one in each primary lead of the main transformer. The other section acts as a differential coil, measuring the difference between current entering and current leaving the transformer primary. This coil also may be separately excited to obtain tripping from other sources as noted later.

The relay has a considerable travel and works against a spring which pulls the moving parts counterclockwise. The normal reset position is approximately in the center of the travel range, the spring holding the moving parts against a latch held in place by an a-c holding coil. Torque caused by energizing either set of motor coils moves the relay clockwise. Early in the travel the *A* and *A1* contactors are actuated. If torque remains, contact *B* is energized at the extreme clockwise travel. If the holding coil and its latch be released and torque removed, the spring rotates the moving parts counterclockwise to extreme position, actuating the *B* and *C* contacts.

If a surge be caused by the starting current when energizing the transformer, the slight resultant movement of the relay takes place without tripping the *A* group of contacts, and the relay resets automatically.

If a ground (including one from motor arcover) occurs in the traction motor circuits, current will circulate through the ground resistor and current transformer connected to the midpoint of a reactor between *D* and *E* taps of the transformer. This sends a corresponding current through the differential coil of the relay and causes it to travel far enough to actuate the *A* group of contacts. These open the motor line switches and incidentally all auxiliary contactors, thereby clearing the trouble, and also operate a buzzer and light an indicating lamp at each operating position. As soon as the trouble is cleared, relay torque is removed and the moving parts reset automatically, but the *A* group of contacts remain tripped. These can be reset remotely by the control switch at the operator's position.

If a ground occurs in the secondary of the main transformer or in the connected bus bars or switches, torque is similarly developed by the relay through the grounding current transformer connection. This time the *A* contacts open nothing that will clear the trouble and the relay continues until the *B* contact closes and throws the main ground switch. This removes voltage from the locomotive and causes the holding coil and latch to drop. The ground current, however, flows through one primary current transformer only and keeps torque on the relay. Only when both voltage and current have disappeared can the relay retract under the spring action to the fully tripped position which lowers the pantographs. The relay then must be reset manually.

If a ground occurs in the main transformer primary, the relay differential coil is excited directly from the 2 primary current transformers, and the operation is the same as in the preceding paragraph.

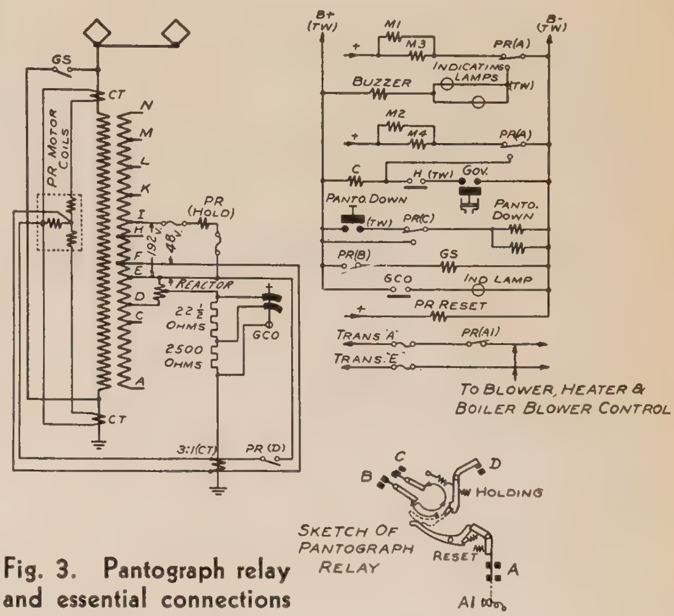


Fig. 3. Pantograph relay and essential connections

B+ positive wire
+ positive from apparatus not shown
B− negative wire
C− compressor contactor coil
CT current transformer
GCO ground cut out switch
Gov compressor governor
GS ground switch
H back circuit interlock
M1, 2, 3, 4, motor line switch coils
PR pantograph relay
(TW) train wire

A heavy primary overload will cause the relay to operate directly through the action of the overload coils. The same sequence of contact operation again takes place.

If on any of these faults the primary current should be so great that the feeder breakers open before the relay has time to close the ground switch, this removes the fault and the relay torque, and retraction takes place lowering the pantographs the same as under the other conditions.

If in any case the engineman finds or believes that the fault is merely a single ground, 2 extra positions of the ground cutout switch (*GCO*) are available. These insert extra resistance in the grounding current transformer circuit to limit the flow of current resulting from the ground fault. It may be possible to run the locomotive to the terminal on one of these connections, but a warning lamp will burn to indicate that operation is taking place partly or wholly without fault protection.

If a succession of surges and interruptions occur, the relay may trip and retract beyond the reset position during an interruption. Return of power at any time before the pantographs start to lower will apply, through the *D* contact, 48 volts to the differential coil and cause the relay to motor back and reset automatically, with no indication to the crew.

Protection thus is afforded under most fault condi-

tions. Only when the locomotive apparatus cannot clear a fault is the ground switch allowed to close, and never are the pantographs lowered so long as current is being taken from the trolley wires.

Port Washington Power Plant Design

Design features of the Port Washington power plant serving the Milwaukee area are described in this article, which covers both steam and electric equipment. Summaries of certain economic studies which formed the basis for decisions are included, but no statistical information on the various pieces of equipment is given. The initial installation includes an 80,000-kw unit, utilizing 1,230-lb steam pressure, and 825 deg F steam temperature.

By
G. G. POST
FELLOW A.I.E.E.

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THE PORT WASHINGTON generating station of The Milwaukee Electric Railway and Light Company, now under construction is located on the west shore of Lake Michigan at East Port Washington, Wisconsin, 28 miles north of Milwaukee. The station's initial capacity will be 80,000 kw (one unit) with a possible ultimate capacity of 400,000 kw (5 units). The outstanding feature will be its unit design, that is, there will be a single boiler for each single turbine-generator and also one set of transformers, one 132-kv transmission line, and one set of auxiliaries for each unit. The next most important advancement is the adoption of 825 deg F temperature for both throttle and reheat.

Selection of Site

Load growth made it apparent in 1928 that generating capacity would have to be added to the Wisconsin-Michigan system of the North American Company in order to maintain the proper relation between system capacity, peak demand, and reserve capacity. The selection of a site resolved itself into a search for one which would most nearly fulfill the following requirements:

1. Be north of the Milwaukee metropolitan area better to insure continuity of service. (The existing major generating station, Lakeside, is south of Milwaukee.)
2. Be located as close to the load center as practicable.
3. Be adjacent to Lake Michigan where the condensing water supply is ample and cold.
4. Be at a location where harbor facilities for lake boats have been established or could be provided at reasonable cost. In the Milwaukee area, water-borne coal has a distinct advantage over all-rail coal, due to the decided and abrupt railroad rate increase on coal in passing through the Chicago district.
5. Be at a location to which large industries might be attracted so that these could be served with energy directly from the station bus bars.
6. Be located so that connections to railroad lines (preferably the company's own) could readily be made, if in the future, combination of coal prices and freight rates should become such as to give rail-borne coal an advantage over water-borne coal.

Port Washington was the only place that met satisfactorily all of these requirements. It will have a coal dock which will eliminate the intervening rail haul with its attendant costs. The effect of this will be to lower its fuel cost about $2.59 per hundred million Btu below that of the Lakeside plant.

Determination of Size

In determining the size of the plant and of the units desire to make it possible to coöperate with industrial concerns that might wish to locate in the vicinity of the plant was an important factor. Because of its harbor, dock, and railroad facilities, Port Washington offers to new industries advantages far superior to those that can be found anywhere else in the vicinity of Milwaukee. Because of this it was felt that it would not be beyond reason to contemplate the possibility of industrial development in the vicinity of the plant to the extent of about 150,000 kw. The fact that Lakeside's last 2 additions were of 75,000 kw capacity each, that normal load in 1928, when Port Washington was originally planned, had been increasing at the rate of nearly 40,000 kw per year, and that there was a possibility of a large industrial load in addition to the normal growth, prompted the decision to install 80,000 kw initially at the new station.

Mercury-Steam Cycle Consideration

The possibility of large industrial plants locating in close proximity to the power station, some of which might require large amounts of process steam in addition to their electrical demands, suggested that serious consideration be given the merc ry-steam cycle. For a given process steam demand the mercury cycle can generate over twice as much by-product electrical energy as can a straight steam cycle, or conversely, the net heat consumption in Btu per switchboard kilowatt-hour would be considerably less with the mercury cycle than with a

Essentially full text of "Design Features of the Port Washington Power Plant" (No. 33-68) presented at the A.I.E.E. summer convention, Chicago, Ill., June 26–30, 1933.

straight steam cycle if the kilowatt-hour outputs were the same. On the basis of straight condensing plants of equal capacity (100,000 kw) it was found that the mercury-steam cycle in order to equal the 1,200-lb steam cycle in total annual costs would have to be operated at an annual load factor on the plant of at least 65 per cent. At lower load factors the 1,200-lb steam cycle showed a saving. For the particular project under consideration, the 1,200-lb steam cycle showed a saving in investment costs of $18.74 per kilowatt while the mercury cycle showed a gain of 2,550 Btu per kilowatt-hour in station heat consumption. With coal at $3.80 per ton and fixed charges taken at 13 per cent the total annual costs (including fixed charges) would be the same at $63^1/_2$ per cent load factor, while with coal at $3.60 per ton they would be the same at 67 per cent load factor. In these calculations allowances have been made for the smaller amount of auxiliary power and the lower capacity of condensing water and coal handling and preparation facilities required by the mercury cycle. It is obvious that with lower coal costs the money saving due to saving a certain quantity of coal becomes less and the installation of the more expensive mercury equipment becomes more difficult to justify.

Table I—Comparison of Actual 1,200-Lb Generation With 300-Lb Generation at Lakeside, 1929

Economy		
Station generation	Million kwhr	993.9
Station output	Million kwhr	948.7
Generation by 1,200-lb cycle	Million kwhr	236.0
Per cent of generation by 1,200-lb cycle		23.8
Overall station heat consumption	Btu/kwhr net	14,882
Heat consumption of an all 300-lb plant	Btu/kwhr net	15,400
Heat consumption of an all 1,200-lb plant	Btu/kwhr net	13,225
Heat saving on 1,200-lb generation	Btu/kwhr net	2,175
Per cent saving of 1,200-lb over a new 300-lb plant = item 8 divided by item 6		14.12
Total 100 million Btu saved = item 3 times item 8 divided by 100,000,000		5,133
Cost of fuel per 100 million Btu		$17.41
Total saving for 1929, 1,200 lb over 300 lb		$ 89,365
Investments		
Greater investment cost of 1,200-lb equipment over 300 lb. (per unit)		$200,000*
Greater annual fixed charges at 13 per cent		$ 30,400
Net Saving		
Net saving for 1929, 1,200-lb cycle over new 300-lb cycle		$ 58,965

Actual operating statistics showed that Lakeside's 1,200-lb cycle had saved 14.12 per cent in coal over that which would have been burned had 300-lb equipment been installed. Maintenance costs were no higher and, except for slightly higher fixed charges, the fuel savings indicate the net savings.

*Second unit started in commercial operation November 1, 1929.

It was concluded that the mercury cycle should not be adopted for the initial section of the plant for the following reasons:

1. The net savings, if any, which the mercury cycle could show over the 1,200-cycle were small.
2. The untried portions of the fundamental parts in the mercury equipment might cause an outage when the capacity could not be spared for any appreciable time especially not for correcting developmental defects.
3. The mercury cycle could be installed in succeeding units very readily, should these experimental matters prove successful.

At the time of making the mercury-steam study, indications of future price trends both of fuel and construction materials were taken into consideration. Recent trends have been along the lines assumed and have not altered the conclusions reached.

Selection of 1,200-Lb Steam Cycle

The design for the Port Washington plant has as its underlying basis the design and operating experiences of the Lakeside plant. Lakeside's first 1,300-lb boiler was placed in operation in October 1926. In October 1929, its second high pressure boiler went into service. By the time that a decision on the pressure for the Port Washington plant had to be made, $3^1/_2$ years of operating experience had been had with the Lakeside equipment. The availability factors for the last 2 of these $3^1/_2$ years on high pressure boilers were 84.3 per cent and 88.5 per cent, respectively. (It may be interesting to record that during 1932 the availability for the 4 high pressure boilers at Lakeside averaged 93.7 per cent.) A careful analysis of the operating statistics for 1929, the last full year before making decisions for Port Washington, showed that Lakeside's high pressure system had in that year effected an actual net saving of $58,965 over straight 300-lb equipment of the latest and the most modern design. The actual fuel saving resulting from 14.12 per cent less coal burned amounted to $89,365 against which was made an offset of $30,400 for annual fixed charges on the larger investment; maintenance costs being the same for 1,200 lb as for 300 lb. (See Table I.)

These economy and reliability figures definitely established 1,200-lb pressure as being far superior to 300 lb, 300-lb pressure being used in this comparison because the existing equipment in the plant, before the installation of the 1,200-lb equipment, was built for it. But in order to exhaust all possible claims for intermediate pressures, a comparison was made between 600 lb and 1,200 lb. The results, shown in Table II, indicated that the 1,200-lb cycle would save $36,754 annually over the 600-lb cycle in the initial installation at Port Washington, after deductions had been made for fixed charges on the greater investment required. This table is based upon reheating to same temperature for both pressures.

Table II—Comparison of 1,200-Lb Generation With 600-Lb Generation, Estimated for Port Washington

Economy		
Estimated annual generation for initial installation 80,000 kw at 60 per cent annual load factor	Million kwhr	421
Saving in heat consumption by 1,200-lb cycle over 600-lb (average all loads)	Btu/kwhr	856
Annual saving in favor of 1,200 lb	100 million Btu/yr	3,610
Cost of fuel per 100 million Btu		$14.82
Total annual fuel saving, 1,200 lb over 600 lb		$ 53,500
Investments		
Greater investment for 1,200-lb boiler room equipment		$147,168
Greater investment for 1,200-lb turbine room		$ 19,300
Lesser investment for 1,200-lb turbine room equipment		$ 20,000
Lesser investment for 1,200-lb station tunnels, circulating water system, and coal handling system		$ 17,650
Net greater investment for 1,200-lb installation		$128,818
Annual fixed charges on greater 1,200-lb investment at 13 per cent		$ 16,746
Net Saving		
Net annual saving of 1,200-lb installation over 600-lb installation of 80,000-kw capacity		$ 36,754

In comparing the economies of 1,200-lb generation with 600 lb, a considerable saving in fuel was found. This, together with the unexcelled reliability record of Lakeside's 1,200-lb equipment decided the issue in favor of 1,200 lb

Consideration of the possibilities of the Benson cycle showed that it held no inducements at this time. Efficiency gains from going beyond 1,200 lb were found to be slight because of rapidly increasing feed pumping costs and steadily decreasing energy gains. The savings shown in Tables I and II, together with satisfactory overall operating experiences at Lakeside, were sufficient to warrant the adoption of 1,200 lb for Port Washington.

Table III—Comparison of 825 Deg F and 750 Deg F Temperature at Both Throttle and Reheat Estimated for Port Washington

Economy	
Estimated annual generation for initial installation, 80,000 kw at 60 per cent annual load factor..................Million kwhr	421
Saving in heat consumption, 825 deg over 750 deg..Btu/sw. bd. kwhr	300
Annual Btu saving, 825 deg over 750 deg..........100 million Btu	1,263
Cost of fuel per 100 million Btu...............................	$14.82
Total annual fuel saving, 825 deg over 750 deg..................	$ 18,720
Investments	
Investment saving of 825 deg due to lower heat consumption....%	2.5
Unit investment to which heat saving applies...........$ per kw	47.30
Total investment saving of 825 deg = $47.30 times 80,000 times 2.5 per cent...	$ 94,600
Total investment saving assuming 75 per cent of total saved.......	$ 71,000
Additional investment saving in 2 steam drums, due to lesser storage required..	$ 5,670
Additional investment saving due to deferring replacing last rows of blades because of lesser moisture in exhaust.................	$ 10,920
Total investment saving, 825 deg over 750 deg..................	$ 87,590
Greater investment cost of 825-deg turbine......................	$ 89,000
Greater investment cost of 825-deg valves and fittings............	$ 8,000
Greater investment cost of 825-deg superheater and reheater......	$ 18,760
Total greater investment cost, 825 deg over 750 deg..............	$115,760
Net greater investment cost, 825 deg over 750 deg (item 16 minus item 12)..	$ 28,170
Net Saving	
Annual fuel saving, 825 deg over 750 deg........................	$ 18,720
Annual fixed charges on greater investment at 13 per cent.........	$ 3,650
Net annual saving, 825 deg over 750 deg........................	$ 15,070

An increase in operating temperature to 825 deg F from 750 deg F for both throttle and reheat showed a 2.5 per cent improvement in station performance. When the saving was capitalized on the basis of reducing equipment costs in the boiler room, it offset the increased cost of the turbine, valves and fittings and showed a substantial net saving for the higher temperature.

Selection of 850 Deg F Maximum Steam Temperature

Among the improvements over Lakeside which were considered was the use of a higher steam temperature. Superheater manufacturers, valve, pipe, and also turbine makers were consulted. All expressed their willingness to coöperate and subsequently quoted prices on equipment necessary not only to produce 825 deg F at the turbine throttle and reheat point, but to maintain it continuously; 850 deg F was specified as the maximum. The increase of 75 deg F in actual operating temperature (Lakeside's is 750 deg F) brings the total steam temperature up to the point where ordinary steels cannot be used in the turbine. Alloys require greater investment particularly in large turbines where they had not been previously applied to the extent that they had been in steam superheating equipment and in valves. The net greater cost of 850 deg F equipment totaled $28,170 in investment. With fixed charges taken at 13 per cent, the annual rate amounted to $3,650. The fuel saving on the other hand amounted to $18,720 per year, resulting from an improvement of 2.5 per cent in station heat consumption rate. The net saving therefore was calculated to be $15,070 per year. The greater investment resulted from a more expensive turbine, greater cost of valves and fittings, and greater cost of superheaters and reheaters. These greater costs were offset by investment savings in boiler plant equipment due to the smaller amount of steam required, less water storage required in steam drums, and by deferred expenditure for replacing the last row of turbine blades due to less moisture in the exhaust steam. (See Table III.)

A higher steam temperature than 825 deg F at the turbine throttle with no reheat was considered purely experimental because it involved untried alloys. Creep in metals is hardly a consideration at 825 deg F, but at 1,000 deg F or thereabouts, it is extremely important. A throttle temperature of 825 deg F with reheat at the same temperature is a reliable, non-base-load combination, one that is made particularly attractive through the application of radiant superheating and reheating surfaces in the same furnace.

Lakeside's operating experiences with reheat are positive proof that variable loads are easily and safely carried. Reheat introduces minimum complications into the cycle.

One Turbine, One Generator, and One Boiler

A previous study had shown that one large turbine generator would save $7.15 per kilowatt over 2 half-size units in investment costs (turbine generators, foundations, turbine room building, electrical equipment, and switch house) and about $25,000 per year in operating costs due to a better rate of heat consumption. These savings were considered sufficient to warrant the installation of an 80,000-kw unit rather than 2 40,000-kw units. Incidentally an 80,000-kw machine would match almost exactly the 90,000-kva transmission lines which had been adopted for the Milwaukee district. (See "The 60-Cycle Primary Transmission System of The Milwaukee Electric Railway and Light Company and Associated Companies in Wisconsin and Upper Michigan," by C. D. Brown and E. W. Hatz; A.I.E.E. paper No. 32M3.)

Most of the original 1,200-lb installations in this country consist of 1,200-lb non-condensing turbines superimposed on existing 300-lb stations. In such installations, of course, new full capacity 1,200-lb boilers were required but the turbines were of comparatively small generating capacity. The economy of such installations due to having to maintain a practically constant pressure at the exhaust of the high pressure turbine for all loads, drops off rapidly in going from full load to partial load. Multiple-valve admission to the high pressure turbine has been used as a partial means of overcoming this difficulty, but the process effects a saving in the high pressure turbine only, whereas the largest part of the loss occurs at the exhaust of this turbine.

If the exhaust pressure is permitted to vary accord-

ing to load through the use of so-called compound operation, savings of considerable magnitude can be made. Such operation naturally would have to be followed in a station which had boilers generating steam at but one pressure. The high pressure turbine, however, could still remain segregated from the low through the adoption of a cross-compound machine. There then would be 2 separate turbines each with its own generator, a combination which has the advantage of keeping the low pressure turbine in service when trouble is encountered in the high pressure turbine. Should the low pressure section be forced from service at any time, the entire unit would be down and because of this fact a reserve equal to the capacity of the whole unit must be kept available at all times. The ability to operate the low pressure section at times of high pressure turbine outage, therefore, loses much of its significance. Besides, the reserve capacity in most cases can be operated at an economy very close to that of the low pressure section alone. The advantages of tandem compounding on the other hand are such as to win approval; they are, net investment savings of $1.12 per kilowatt resulting from (1) a lower cost of the turbine-generator itself, (2) fewer electrical connections because of having only one generator, (3) less building volume, and (4) a credit for a smaller turbine room crane because of a narrower turbine room.

Many of the arguments presented against the cross compound unit apply to the steeple compound unit also, although the economic advantage of the tandem over the steeple is not as great as it is over the cross compound. Inconvenience in operation and maintenance also were factors in deciding against the steeple compound unit.

After having established the size and type of the turbine to be installed, the next consideration was the number, size, and type of boilers. Detailed comparisons were made on the installation of 2 boilers of small size (345,000 lb per hour capacity) and of 1 boiler of large size (690,000 lb per hour capacity).

One boiler was selected rather than 2, because:

1. An investment saving of approximately $250,000 could be made.
2. The operation would be simpler due to not having to apportion the exhaust steam from the high pressure section of the turbine to each of the 2 reheaters.
3. The presence of an 80,000-kw turbine generator on the system would require 80,000-kw reserve in any event. Therefore, no additional losses in capacity would occur due to boiler outage.

At Lakeside, 3-drum bent-tube type boilers with comparatively large low-heat release furnaces had unprecedented reliability records. Certainly records of this nature could not be ignored in making selections for the Port Washington boilers. This fact notwithstanding, all arguments for the single-drum straight-tube boiler and high-heat release furnace were obtained and carefully weighed. Prices were secured and tentative layouts prepared so that an unbiased opinion as to their merits might be formed.

Exponents of the straight-tube boiler design with its complementary equipment maintained that with it a better proportioning of all of the heat reclaiming surfaces could be secured together with a lower overall investment cost. The use of less of the comparatively high cost boiler surface and more of the less expensive economizer surface formed the basis for their arguments. They also maintained that less building volume would be needed. Contrary to expectations, the latter was not found to be true for

Table IV—Comparison of Boiler Designs for Port Washington, Initial Installation

	Bent-Tube Boiler Low-Heat Release Furnace	Straight-Tube Boiler High-Heat Release Furnace
Total investments in boiler, furnace, superheater, reheater, economizer, air-heater, feeders, burners, and milling equipment*	$937,137	$838,805
Greater investment of bent-tube boiler	98,332	
Greater annual fixed charges at 13 per cent	12,783	
Increased operating costs		
a. Greater pressure drop in superheater		$ 156
b. Greater pressure drop in reheater		1,920
c. Loss of heat in molten ash		1,780
d. Lower overall boiler efficiency		6,370
e. Poorer availability		3,900
f. Lower reheat temperature		2,720
g. Greater furnace maintenance cost		5,700
h. Total greater operating costs		$ 22,546
Net annual saving of bent-tube boiler with low-heat release furnace		$ 9,763

The bent-tube boiler with a low-heat release furnace not only will produce an annual saving of $9,763 but will also permit the use of radiant superheat and reheat surfaces within the furnace, and afford other operating advantages.
*Building not included because costs would be identical.

Port Washington conditions, principally because of a 10-ft higher building which would be required. It was true, however, that a small saving in investment was shown with the straight-tube boiler layout over that of the bent-tube type but this saving was more than offset by operating losses. Table IV summarizes these gains and losses. Then too, high-pressure economizers (1,600 lb) which are an essential part of the straight-tube boiler layout were considered a potential source of trouble. As explained later, economizers were eliminated entirely from the Port Washington design.

It was concluded finally to adopt the bent-tube type boiler fired from one side only with a low-heat release hopper-bottom furnace beneath it. Besides the economic gains and the possibility of eliminating economizers, the following additional reasons influenced its selection:

1. About 50 per cent more water storage space is available; this is very important when only a few minutes total storage is available.
2. Tubes being nearly vertical permit rapid water circulation which eliminates wide variations in drum-water levels throughout the load range.
3. Dry steam is obtained since the rear drum acts as a dry drum, it having little steam released from the water it contains.
4. Water wall connections can be made easily because of accessibility of the drums.
5. Suspended solids in the boiler water are removed effectively in the lower drum.

Furnace

The slag-tag furnace, which was given some consideration, is a high-heat release furnace of relatively small size because the temperature in the furnace

must be kept sufficiently high to maintain the ash in a molten state. The small size and high temperature preclude the use of radiant superheaters and reheaters. The latter are desirable because their inherent characteristics are such as to give automatically the most economical operating conditions at all loads. Superheaters and reheaters of the all-convection type give decidedly variable steam outlet temperatures with variations in load on the boiler necessitating desuperheating at the higher loads. This was considered objectionable because of the general unreliability of the desuperheating process. No desuperheater is required with the radiant surfaces in the Port Washington station design. On the other hand, large furnaces with a low rate of heat release (15,000 Btu per cubic foot per hour, maximum) are conducive to low maintenance costs and high availability. With steel walls, consisting of steam and water cooled surfaces on all 6 sides, there can be no wall erosion. Radiant superheater and reheater surfaces for side and rear walls and water tubes for the front wall and the ash screen were the final answer to the furnace problem after all advantages and disadvantages of other combinations had been carefully balanced.

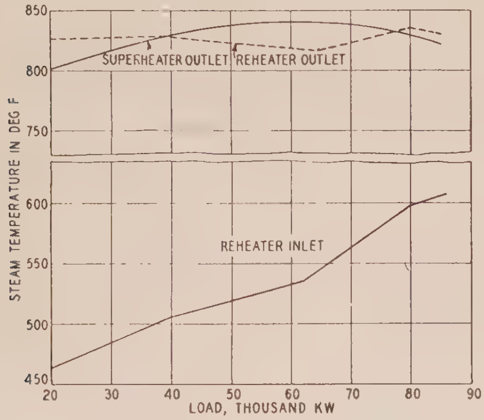

Fig. 1. Uniform steam outlet temperatures such as these, from both the combination radiant and convection superheater, and the radiant reheater, over a load range from full to quarter load will tend to produce high over-all plant efficiency

Radiant Superheater and Reheater

Selection of radiant heat absorbing surfaces for superheater and reheater rather than all-convection surfaces was prompted by economic considerations as well as the adaptability of these surfaces to the low-heat release furnace mentioned in the previous paragraph. More uniform steam temperatures over wide load ranges can be obtained automatically and thus the overall station economy can be improved. This is particularly true at low loads when all other factors in the system are working toward poorer economy. By virtue of the higher superheat the turbine efficiency is maintained higher than it would otherwise be at the lower loads.

The superheater selected has a radiant section and a convection section. The steam will pass first through the former and then the latter. With this combination the steam temperature to the turbine throttle will vary only from 830 deg F at full load to 802 at quarter load. The reheater on the other hand is radiant entirely and its outlet temperature will vary from 834 at full load to 827 at quarter load. (See Fig. 1.)

Air Heater and Economizer Considerations

Economizer and air heater surfaces (all waste heat reclaiming surfaces for that matter) are closely related to the type of cycle adopted for the station. In the case of Port Washington, a tentative cycle was decided upon at the time of placing the turbine contract. This called for the use of extraction heaters at 5 points. A comparison between 4 extraction heaters plus an economizer-air heater combination, and 5 extraction heaters plus an air heater only, indicated that a net annual saving of $7,429 could be made through the use of the latter. The comparison of these 2 methods is summarized in Table V, based upon 4 extraction heaters plus an air-heater only, the figures being estimated for the Port Washington plant. The major portion of the saving shown is effected by the 1.3 per cent better heat rate of the turbine due to the fifth heater. Although the addition of an economizer would reduce the flue gas temperature 25 deg F and thus make a substantial saving in boiler efficiency, the fixed charges on the greater investment for the economizer and piping (after taking credit for the smaller air heater) and the maintenance costs on the economizer would more than offset this gain. Five-stage heat-

Table V—Comparison Between 4 Extraction Heaters Plus Economizer-Air Heater Combination and 5 Extraction Heaters Plus Air Heater Only

	Gain	Loss
Four-Stage Heating and Economizer		
Saving due to lowering of flue gas by 25 deg F	$4,520	
Maintenance cost on economizer		$2,000
Pumping cost for pressure drop through economizer		120
Fixed charges on greater investment cost for economizer and piping after deducting credit for smaller air heater, $35,800 at 13 per cent		4,654
Total costs	$4,520	$6,774
Net annual loss for economizer		2,254
Five-Stage Heating		
Better heat consumption rate due to fifth-stage heaters—112 Btu per kwhr	$6,995	
Maintenance cost on fifth-stage heaters		400
Pumping cost for pressure drop through heaters		120
Fixed charges on investment in fifth-stage heaters, also necessary piping, $10,015 at 13 per cent		1,300
Total costs	$6,995	$1,820
Net annual gain for fifth-stage extraction heaters	5,175	
Net Comparison		
Net gain due to fifth-stage heaters	$5,175	
Net loss due to economizer	2,254	
Net annual difference in favor of fifth-stage heaters	$7,429	

Economizers ordinarily are thought of as equipment used to enhance power plant operating efficiency. This tabulation shows that extraction heaters do this more effectively, and with far less need for worry about operating difficulties under the higher pressures encountered.

ing with an air-heater but with no economizer was therefore decided upon.

Bin and Feeder Versus Unit System

In determining the method of firing to be adopted, a thorough investigation was made into the adaptability of the unit system and of the bin and feeder system to the contemplated plant layout. The results showed that the boiler efficiency obtainable with the unit system was about equal to that of the bin and feeder system with no gain for either on such items as carbon loss, uniform grinding, etc. There were, however, inherent advantages of the bin and feeder system which influence total station economy rather than only boiler efficiency and it was these which decided the matter in its favor. The most outstanding of these advantages are:

1. Greater reliability. With the unit system any outage of a mill for any reason will cause a reduction in capacity of the boiler or complete outage of the boiler. Whenever a reduction in load occurs, it must be picked up by some standby or less efficient station, and a loss of 0.1 per cent in economy might result.

2. Flexibility. The low rating limitation of the unit mill is absent entirely from the bin system. This is particularly important at times of starting when low furnace temperatures are desired to prevent damaging superheater tubes.

3. Mill drying with flue gas can be used in the storage system to advantage, while on the other hand it cannot be used efficiently in the unit system. Venting flue gases back into the furnace is not conducive to efficient combustion and to the maintaining of proper flame control. With flue gas drying in a storage mill, 6 per cent of the total flue gas discharges to the stacks at a temperature 200 deg F lower than the usual exit temperature. In addition, air heater performance is improved due to the greater mean temperature difference and the lesser heat absorption in the air heater. After the flue gas mill drying system has been charged with the small coal vent loss, it shows a net gain of 0.5 per cent over using hot air and venting to the furnace.

4. Coal feed can be regulated more closely with the storage system resulting in the maintenance of high average CO_2 and fine control of excess air. With radiant superheaters and reheaters this is important. Coal feed variations of 10 per cent as are common with the unit system without hand adjustment can cause a 50 deg variation in reheat temperature and 0.6 per cent decrease in station economy.

5. Coal feed control at Lakeside where the storage system is used has been found to be so regular that boiler pressure can be regulated to within 5 lb of a standard. With the unit system, the pressure variations might be on the order of 50 lb. The difference of 45 lb in pressure at the turbine could cause 0.6 per cent difference in economy.

6. When using air drying with unit mills the heated air to the mill must be tempered with room air. This reduces the amount of air to be taken through the air heater and reduces the boiler efficiency about 0.3 per cent below that of a storage system boiler where flue gas drying is used.

7. Automatic combustion control is much more positive on a storage fired boiler than on a unit fired one. With the latter, difficulties are encountered in coördinating the mill speed, primary air volume, and sizing of the pulverized coal particles with the requirements of the boiler. Lower overall efficiencies will result.

These advantages, totaling 2.1 per cent in station economy, can be credited to the storage system. Investment costs were found to be 74 cents per kilowatt lower for the unit system. Labor, maintenance, and power were slightly in favor of the unit system. An important point in favor of the storage system is that most of its motors can be shut down at the time of the station peak. The unit system on the other hand requires peak electrical demand for auxiliaries coincident with the peak station demand and to provide the same margin in capacity, an equivalent in generating capacity must be installed at the same station or elsewhere.

Another important advantage of the storage system is the safety to personnel and equipment occasioned through the use of flue gas for mill drying. A 12 per cent volume of CO_2 (an inert gas) is maintained in the mill system and collectors, so that danger of fire or of an explosion from smoldering coal is lessened materially.

The analysis, of which Table VI is a summary, showed the bin and feeder system to effect a net annual saving of $11,062 and this, together with certain operating advantages, formed the basis for its adoption.

Table VI—Comparison of Storage System and Unit System of Pulverized Fuel Firing, Estimated for Port Washington

Economy		
Estimated annual generation for initial installation, 80,000 kw at 60 per cent annual load factor	Million kwhr	421
Saving in heat consumption, storage over unit	%	2.1
Btu saving, storage over unit	Btu/kwhr	252
Annual Btu saving, storage over unit	100 million/yr	1,061
Cost of fuel per 100 million Btu		$14.82
Total annual fuel saving, storage over unit		$15,750
Labor, Maintenance and Power		
Greater cost of labor (1 extra man) storage over unit		$ 2,400
Greater cost of maintenance, storage over unit		$ 950
Lesser cost of power, storage over unit		$ 575
Net greater operating costs, storage over unit		$ 2,775
Investments		
Greater investment cost in mills, feeders, burners, motors, starters, duct work, foundations, air compressors, fuel bins, etc., storage over unit		$59,112
Greater annual fixed charges at 13% storage over unit		$ 7,685
Station Peak Capacity		
Greater kilowatt demand of unit system motors at time of station peak		592
Value of 592-kw station capacity at $75 per kw		$44,400
Lesser annual fixed charges on station capacity, storage over unit		$ 5,772
Net Saving		
Net annual saving, storage system over unit system (item 6 minus item 10 minus item 12 plus item 15) =		$11,062

The battle of storage versus unit system of pulverized fuel firing was waged for many weeks in the company's engineering department before the storage system was awarded the decision. Its merits include not only an annual saving of $11,062, but greater reliability and flexibility, as well as safety, due to the possibility of using flue gas mill drying with it.

Extraction Heaters and Feed Pumps

After having determined the number of extraction heaters to be used in the heat cycle, a very important decision had to be made in regard to the location of the boiler feed pumps in the cycle. The high pressure boiler feed pumps at Lakeside, although they had been operating continuously for over 4 years and had never been the cause of 1,200-lb equipment outage, had demanded considerable attention and were creating maintenance costs which were considered too high. Their operation as a whole was rather delicate. An investigation showed the cause of the difficulties to be fluctuations in feed water temperatures which set up uneven expansion and contraction in the various component parts of the pumps causing clearance variations, packing leaks, etc. The maximum feed water temperature delivered to the Lakeside 1,600-lb pressure pumps is 360 deg F while it might go down to 300 deg F or slightly below at light loads. The pumps at Port Washington, if they are placed on the discharge side of the extraction heaters, would be required to handle water to as high as 432

deg F temperature at full load and as low as 290 deg F at quarter load, a condition much more severe than that at Lakeside. Should they be located after the second heater, however, and made to discharge through the heaters at the remaining 3 extraction

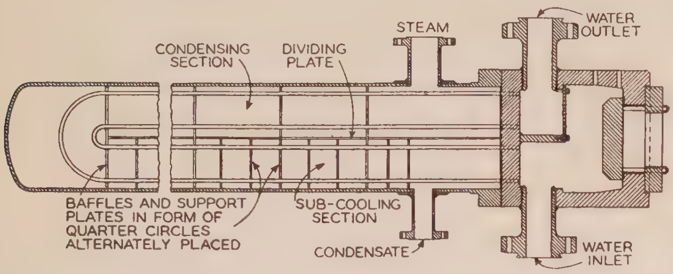

Fig. 2. Bolted heads with gaskets and stay-bolts are eliminated in this extraction heater built for a water pressure of 1,600-lb

points, the temperature of the water entering the pumps could be held constant at 200 deg F. The manufacturers of the feed pumps were in hearty approval of the suggestion that the lower temperature be used in spite of the relatively low delivery pressure to the suction of the pumps, and promptly quoted on pumps with efficiency quarantees somewhat improved over those at Lakeside. This improvement in efficiency is incidental to the improved reliability of the pumps and to the 12 per cent saving in pumping energy occasioned by the lower specific volume of 200 deg F feed water compared with that of 400 deg F feed water. The somewhat higher cost for the high pressure extraction heaters over the lower pressure type was not nearly enough to offset the advantages mentioned.

Two sets of high pressure extraction heaters will be used, one on each of the feed lines to the boiler. Each feed line will have a separate high pressure pump with a spare pump so connected that it can be substituted in either line. Two feed lines to the boiler will be used because better parallel operation of centrifugal feed pumps can be obtained when discharging through heaters and piping before pressures are equalized. Then, too, it was found economical to use 2 sets of heaters because by-passes around the heaters with their expensive fittings could be eliminated.

Interesting design details involved in the construction of the high pressure extraction heaters are worthy of mention because they have heretofore never been attempted. It is common knowledge that bolted heads with gaskets and stay-bolts are a serious problem in the use of high pressure heaters. These have been entirely eliminated through the adoption of a head made from a solid forging bored out and supplied with an internal head cover, similar to a boiler manhole plate design. (See Fig. 2.)

Steel tubes with U-bends have been decided upon because experience at Lakeside has proved them to be more reliable than brass tubes, and they cost less. Corrosion of the tubes can be prevented entirely by complete de-aeration which is essential in any event in a 1,200-lb pressure plant.

Flash losses between the high pressure heaters will be eliminated by cooling the drains in the lower sections of the heaters before cascading them into the next lower heaters. Separate drain pumps on individual high pressure heaters would be impractical because of having to pump against 1,300-lb boiler pressure. Calculations show an improvement of

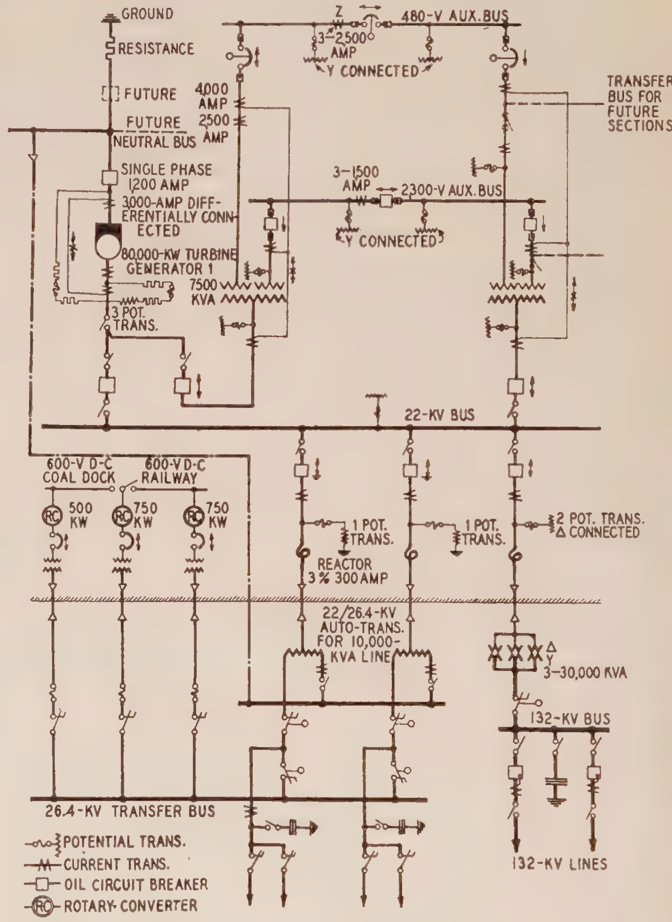

Fig. 3. Single line wiring diagram of the initial installation at the Port Washington power plant

about 0.75 per cent in plant economy through the elimination of flash losses.

Generation at 22,000 Volts

In selecting the generator voltage, the following were considered:

1. No pioneering in generator voltages was desired.
2. A voltage was desired that would enable industries which might locate in the vicinity of the plant to connect their lines to the bus bars as economically as possible.
3. If any economies could be effected in the plant investment and operating costs by using a voltage higher than 13,800 (the Lakeside voltage) such economies should be realized.
4. It would be desirable to adopt a voltage which would permit the connection of the existing 26,400-volt secondary transmission lines of the company with a minimum of expense. This is not a matter of much importance because very little of the energy will be delivered at this voltage. Most of it will be stepped up directly to 132 kv.
5. A voltage was desired that all manufacturers would be willing to use in their machines without resorting to special construction, such as concentric conductors.

The voltage which most nearly met all of these conditions was found to be 22,000 volts. In using this voltage it was found that a saving of 0.3 per cent could be realized in investment and operating costs of generators and electrical equipment over similar costs for 13,800 volts. No saving could be effected by adopting 26,400 volts because equipment in the 34,500-volt class, which is more expensive, then would have been necessary. Because of the adoption of 22,000 volts, it is necessary to use auto-transformers to connect to the lines operating at 26,400 volts.

Indoor Switching Equipment of 22,000 Volts

The main electrical connections of the initial and ultimate installations are shown in Figs. 3 and 4. Whether to build a switch house and install indoor 22,000-volt switching equipment or to install metal clad equipment outdoors was given a great deal of consideration. Regardless of the decision on this point, it was recognized that it would be necessary to build a transformer repair house and control house, which limited the decision simply to the switching equipment itself, main bus bars, reactors, etc. All of the comparative estimates made included the control house and transformer repair building. Estimates were obtained from the manufacturers on various kinds of switching equipment and it was assumed in the case of the outdoor metal clad equipment that there would be a likelihood of a reduction in cost of about 10 per cent during the time that the station was growing from its initial to its ultimate size. It was found that for the initial section the outdoor metal clad equipment would require an expenditure of $6.03 per kilowatt while the vertical indoor isolated phase construction, including building and foundations, would require an expenditure of $5.62 per kilowatt, or $0.41 per kilowatt in favor of the indoor vertical isolated phase arrangement. In the ultimate station, with relatively more switching equipment because of the duplication of switches on certain lines and the use of a ring 22,000-volt bus with reactors, the corresponding figures would be $7.62 per kilowatt for the outdoor metal clad and $5.78 per kilowatt for the indoor vertical isolated phase arrangement, including building a saving in favor of the indoor arrangement of $1.84 per kilowatt. In view of the economies that could be effected and other advantages, such as the greater ease of making changes from the original layout and the use of oil-less circuit breakers in the indoor arrangement, it was decided to put all of the 22,000-volt switching equipment indoors. After deciding upon the use of indoor equipment, it was thought desirable to consider the merits of various kinds of indoor equipment and so cost figures were prepared on indoor 3-pole assembly metal-inclosed equipment. It was found that in the initial installation the metal inclosed equipment would cost $0.17 per kilowatt more than the vertical-isolated phase arrangement and $0.31 per kilowatt more in the ultimate installation. Vertical-isolated phase construction therefore was selected.

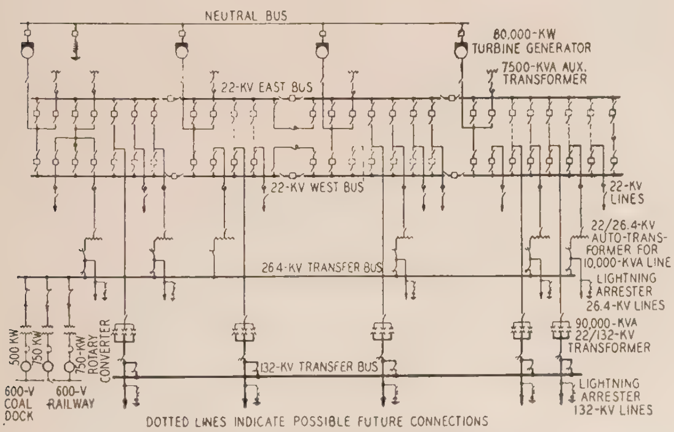

Fig. 4. Single line wiring diagram of the contemplated electrical connections at the Port Washington power plant when 4 80,000-kw turbine generators had been installed

Auxiliary Power Supply System

A-c auxiliary service will be provided by 7,500-kva 3-winding transformers stepping down from 22,000 volts to 2,300 and 480 volts. There will be one transformer connected directly to the leads of each generator and one spare transformer connected to the 22,000-volt bus. Each transformer will supply auxiliaries for its own unit with automatic provisions for transferring the load instantaneously to the spare transformer in case of trouble on the normal supply. (See Fig. 5.) Motors of 100-hp capacity and larger will be supplied at 2,300 volts and motors of less than 100 hp at 480 volts.

D-c service supplied from motor-generator sets with a battery floated across the busses will be used to supply pulverized coal feeders, electrically operated valves, turbine room cranes, elevators, emergency lights, and magnetic pulleys. The only steam-driven auxiliaries in the plant will be one emergency feed water pump and one emergency house service water pump.

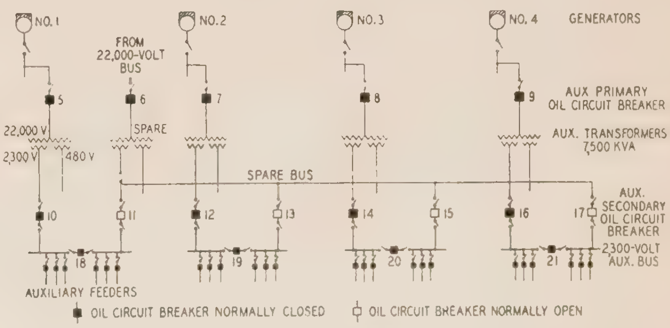

Fig. 5. Single line wiring diagram of connections to principal auxiliaries. Automatic relaying is used to maintain service on the maximum number of auxiliaries possible for a fault at any given location

Corona Loss Vs.

Atmospheric Conditions

In previous investigations of corona loss on electric conductors, variations in loss were observed that were believed to be caused by daily variations in atmospheric conditions. Consequently, a series of tests was made to investigate the effects of humidity, pressure, temperature, and smoke; the results are given in this article.

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SINCE the first corona loss measurements were made, much has been learned about the nature of corona loss on electric conductors. It is known now that corona loss varies with numerous factors; these may be grouped roughly under 3 heads. The first of these has to do with the conductor itself; the loss is known to vary with the diameter of the conductor, the shape of the cross section, the spacing between conductors, and the distance from ground. The second group includes changes in the conductor due to outside causes; under this heading may be classed the effect of dirt and grease on the surface of the conductor. The third group includes all extraneous affecting conditions such as weather, and atmospheric temperature and pressure.

During recent investigations, however, variations in corona loss have been noted which are not accounted for by the foregoing line of reasoning. The only explanation seems to be that it is practically impossible to duplicate daily atmospheric conditions; hence some means of controlling these conditions obviously is highly desirable. Also the study of corona loss would be facilitated were it possible to reduce all results to the same base. With these factors in mind the present work was started early in 1932 at which time the study was undertaken by Victor Siegfried (A'32), a graduate student of Stanford University.

The original equipment consisted, first of all, of an air-tight steel tank 30 ft high and 5 ft in diameter mounted vertically in a corner of the laboratory. An attempt was made to approximate atmospheric conditions inside of this tank. Atmospheric pressures corresponding to various altitudes were obtained by partially evacuating the tank, for which purpose a reversible air pump was used; and the pressure could be varied above or below that of the atmosphere. The test specimen, consisting of a conductor 25 ft in length, was suspended from the end of a brass rod passing through a porcelain high voltage bushing in the top of the tank. A 5-in. lead ball was attached to the free end of the conductor to hold it straight and prevent swinging. The conductor was connected through the brass rod and a shielded lead through a high voltage wattmeter to a 350,000-volt transformer. Losses to the bushing were supplied through the shielding system directly from the transformer and were not read on the wattmeter. In this way only the loss on the test specimen could give a wattmeter deflection. The tank was maintained at ground potential. The high voltage wattmeter and electrical connections are essentially the same as described by J. S. Carroll and B. Cozzens ("Corona Loss at 220–330 Kv," ELECTRICAL ENGINEERING, v. 52, March 1933, p. 178–83).

Besides variations in pressure, an attempt was made to change the temperature and humidity within the tank. Some progress was made in this regard. However, because of the limitations of the original set-up, some additions were made to the equipment in the fall of 1932. The first of these was a circulating system consisting of a 6-in. pipe joining the top and bottom of the tank through a large blower. The blower was belt-driven by a d-c motor making possible a variable speed. The next improvement was to insulate the tank against radiation of heat, leaving the blower as the only radiating surface of the system. As a means of introducing heat into the tank a 7.5-kw heater was placed in the entry between the blower and tank. With this amount of heat concentrated in one spot it became necessary to provide a safety device which would prevent the heat from being applied if the blower were not in operation.

To vary the humidity within the tank, steam was introduced into the circulating system. The boiler used for this purpose was so placed that the steam could be injected directly into the air stream back of the blower. Temperatures within the tank were measured by means of thermocouples projecting into the atmosphere of the tank through air-tight bushings. Temperature measurements were taken at the top and bottom opposite the ends of the conductor. Previous experiments showed that there was no difference between the temperature at the surface of the conductor and the temperature of the air next to the wall of the tank at the same height. The temperature of the outside air also was read by means of a third thermocouple. Humidity within the tank was determined by means of a wet and dry bulb thermometer. Preliminary tests showed that the average temperature within the tank could be maintained at about 140 deg F. There was a difference of several degrees between top and bottom, but the even gradient justified the use of an average temperature in computations.

Humidity was found to have no appreciable effect on corona loss over the range investigated, this included humidity as high as 90 per cent. With the

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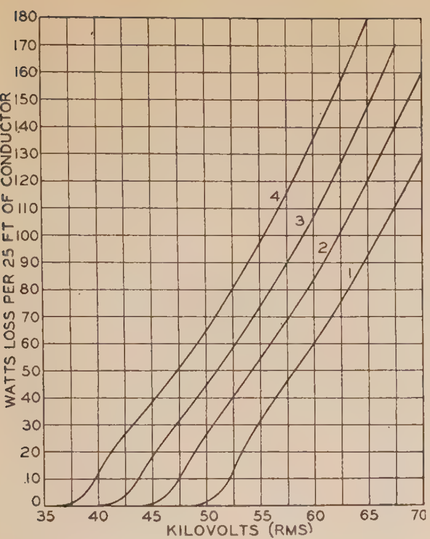

Fig. 1. Corona loss at various pressures; solid copper No. 2 B&S gauge conductor

Curve	Absolute Pressure, Inches of Mercury
1	29.95
2	26.69
3	23.84
4	20.86

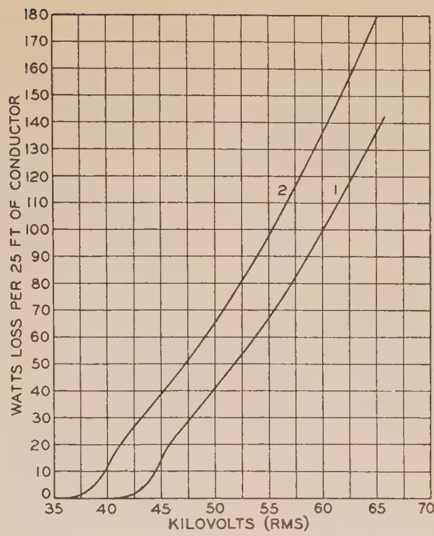

Fig. 2. Corona loss at various temperatures; solid copper No. 2 B&S gauge conductor

Curve 1. 18.85 deg C (65.5 deg F)
Curve 2. 53.25 deg C (127.5 deg F)
Absolute pressure 20.88 in. mercury

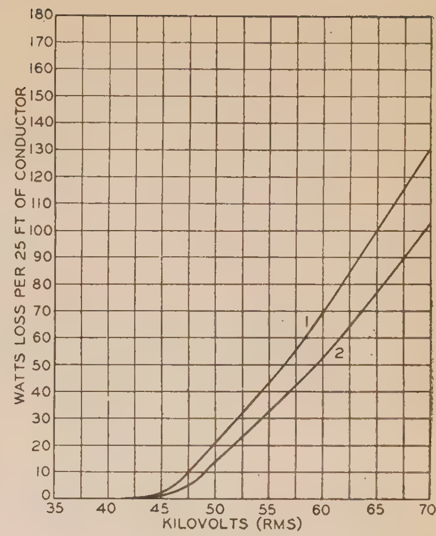

Fig. 3. Effect of smoke on corona loss; 7-strand steel cable, maximum diameter 0.240 in.

Curve 1. Conductor in clear air
Curve 2. Conductor in smoke formed by burning rag soaked in lubricating oil
Temperature, pressure, and humidity constant at the values of the outside air

exclusion of humidity as an affecting factor, it was possible to determine the effect of temperature and pressure in various combinations. Data for several corona loss curves were taken, using a smooth solid copper conductor No. 2 B&S gage; a few representative curves are reproduced in Figs. 1 and 2. It is noticeable that the shape of the curve is not appreciably changed by variations in pressure and temperature. Instead the curve is shifted in the direction of lower voltage as temperature is increased, or as pressure is decreased, or both. The amount of this shift has been found to bear a relation to the change in air density. It has been thought previously that the critical corona voltage is proportional to the air density. Results of these experiments, however, show that the amount of shift due to a given change of air density depends on whether the density was changed by variations in pressure or by variations in temperature. By means of fairly simple computations it may be shown that where the air density has been changed by a variation in pressure the shift of critical corona voltage is proportional to about 70 or 80 per cent of the change in density; and where the change is caused by variation in temperature the shift is approximately proportional to the density change.

In this connection it must be remembered that while the critical voltage is theoretically the voltage required to break the conductor into corona, in practice it is a somewhat fictitious quantity. For this reason it may not be determined with any great degree of accuracy and its usefulness lies only in the locating of the loss curve.

It was thought desirable to study also the effect of smoke on corona loss. First the loss in clean air was measured; then it was measured after introducing into the tank a dense smoke formed by burning a rag soaked in lubricating oil. For these tests a 7-strand steel cable having a maximum diameter of 0.240 in. was used. Results of these tests may be seen in Fig. 3. The effect of smoke was not to shift the curve but rather to change the shape, decreasing the loss 25 to 30 per cent throughout the range of test voltage.

As regards the difference between the effects of temperature and pressure it is supposed that the greater effects of temperature may be accounted for by the change in velocity of the gas molecules. When the density is decreased by decreasing the pressure, a certain percentage of the gas molecules is withdrawn without increasing the velocity of those remaining; whereas, when the density is decreased by increasing the temperature, this same percentage of gas molecules is driven out because of an increase in the molecular velocity. Now, in the latter case, the remaining molecules, having a higher velocity than in the former, may ionize to a greater extent and the loss becomes greater.

In regard to the effect of smoke, the explanation again seems to lie in the consideration of the ion. The charges moving out from the conductor become attached to the smoke particles which being heavy retard their progress; a shielding effect is built up by the immobility of this space charge.

No definite conclusions have been reached regarding the effect of different types of conductor, although both the results of Siegfried and those of the more recent experiments show differences in the curve shapes for the 2 conductors used. Further, the smooth conductor seems to be more sensitive to changes in surrounding conditions.

The pursuit of this investigation carries great promise of interesting and valuable discoveries, and it is hoped that in the near future some definite laws of corona behavior will be established and that some of the problems suggested by the present results may be followed through.

Iron Shielding for Telephone Cables

Among the benefits obtained by the cabling of telephone circuits is the substantial reduction in magnetically induced voltages that can be realized from the shielding action of the lead sheath. Even greater shielding is attainable if the cable is provided with a steel armor or is installed in iron pipe conduit. In this paper is presented a method for the quantitative prediction of the electromagnetic shielding effected by such iron-surrounded telephone cable sheaths, experimental verification of its applicability, and the necessary impedance data for its utilization.

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VOLTAGES of fundamental and harmonic frequencies, induced along communication cables by neighboring power or electric railway systems, can be reduced by the electromagnetic shielding action of the sheath, if this is grounded continuously or at the ends of the exposure.[1] The shielding, particularly at the fundamental frequency, is improved greatly by the provision of a steel tape armor, while a surrounding iron pipe conduit effects a very great improvement at both the fundamental frequency and the higher harmonics.

This paper presents methods for the quantitative prediction of the shielding, expressed by a "shield factor" or the fraction to which a disturbing voltage is reduced. Necessary impedance data are given for numerous iron-surrounded cable constructions and working charts are supplied for the convenient determination of the shielding obtainable with commercially available steel tape armored cables.

On the basis of data presented in this paper, prediction of the shielding to be obtained from steel tape armored cable sheaths or those inclosed in iron pipes is concluded to be both feasible and practical. With internal impedances measurable on short length samples of a chosen construction, the accuracy of prediction is limited principally by the precision to which the disturbing field and the grounding resistances of the cable sheath may be determined. Either of the constructions discussed is capable of effecting a high order of shielding against low frequency induction and practically complete protection from harmonic disturbances. Field observations on installed cables, both tape armored and in pipe conduit, have verified the computational methods presented.

Theoretical Discussion

The term "shielding" designates the action of altering, and usually diminishing, the induction into a circuit or circuit element from charges or currents borne by some other circuit or circuit element. The adjectives "disturbed" and "disturbing" describe these respective systems, the name "shield" or the modifier "shielding" denoting a third system which, by the action of charges or currents set up in it, effects the reduction. A disturbed system so protected is termed the "shielded" system, while the degree of the reduction is denoted by a "shield factor," η—the ratio of the resultant or shielded effect to the initial or nonshielded effect.

The shielding of cabled communication conductors by a grounded sheath is so complete in the case of electric induction that only the shielding action toward magnetic induction need be considered. Further, because of the close proximity and continuous transposition of the wires, the voltages directly induced in the metallic circuit formed by a cable pair are unimportant. Consequently, only longitudinal voltages, observable as voltages between conductors and sheath or ground, remain to be considered. Even with completely metallic communication circuits and under normal conditions in an adjacent power system these longitudinal voltages may be of interest, for, although small, their harmonic constituents may act through unbalances to cause circuit noise. Under abnormal conditions in the power system, the longitudinal voltages of fundamental frequency in the absence of shielding may attain values of a thousand volts or more.

For simplicity the disturbing system will be treated as a ground return circuit, thus simulating a fault condition of a power line or the operating condition of an electric railway. Conclusions resulting from this treatment are equally applicable for corresponding magnitudes of induction from balanced power circuits.

Nomenclature and units used in this paper are as follows:

I_1 = current in disturbing circuit, amperes
I_2 = current in cable sheath circuit, amperes
E_3 = induced or nonshielded voltage in disturbed circuit per thousand feet
V_3 = resultant or shielded voltage in disturbed circuit per thousand feet
η = shield factor, V_3/E_3, numeric
Z_{13} = total mutual impedance between disturbing and disturbed circuits, ohms per thousand feet
Z_{22} = total self-impedance of cable sheath with earth return, ohms per thousand feet
Z_{23} = total mutual impedance between cable sheath and disturbed circuits, ohms per thousand feet
Z°_{22}, Z°_{23} = external components of impedances
z_{22}, z_{23} = internal components of impedances
R = resistance of end ground connections of cable sheath, ohms

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1. For references see bibliography at end of paper.

r_{22} = d-c resistance of cable sheath, ohms per thousand feet
Δr = effective resistance increment for steel armored sheath, ohms per thousand feet
x = internal reactance of armored sheath, ohms per thousand feet
l = exposure length, thousands of feet
G = "leakance" of underground cable sheath, mhos per thousand feet

The longitudinal electric fields set up along both the sheath (2) and the core (3) of a cable exposed to an adjacent grounded disturbing conductor (1) are the same and may be noted by $E_2 = E_3$. The field is formulated as the product of the disturbing current and the mutual impedance between the disturbed and disturbing circuits: $I_1Z_{12} = I_1Z_{13}$. Grounding the sheath at both ends of the exposure results in a current, I_2, which by its counter field, I_2Z_{23}, effects a reduction in the voltage along the core to a value V_3. If the cable is removed sufficiently far from the disturbing conductor so that there is no interaction from this current, there may be written:

$$
\begin{aligned}
0 &= E_3 + I_2Z_{22} \\
V_3 &= E_3 + I_2Z_{23}
\end{aligned} \tag{1}
$$

as the total voltages around unit length sheath and core circuits. Solving:

$$\frac{V_3}{E_3} = 1 - \frac{Z_{23}}{Z_{22}} = \eta \tag{2}$$

Thus, the field along the cable conductors is reduced by the shielding action of the sheath to a fraction η, the shield factor, of that otherwise present.

In order that the shield factor may be low, it is desirable that the self and mutual impedances, Z_{22} and Z_{23}, be of like magnitude and phase. The added reactance and the resistive loss increments due to a surrounding iron armor or pipe, being more or less common to the 2 impedances, are obviously of advantage. A reduction in the d-c resistance of the sheath or the grounding resistances is of benefit since these are components of the self impedance only.

Computation of the shield factors for iron-surrounded sheaths is complicated by the dependence of the self- and mutual impedances upon the sheath current. To consider this effect, it is convenient to resolve the impedances into their "external" and "internal" components. Of these, the latter are properties solely of the conductor, comprising the d-c resistance (for the self-impedance only), resistive increments due to iron losses, and reactances due to linkages of such fluxes as exist within the outer radius of the cable. The external components, which are dependent upon the radius of the cable, the placement with respect to the earth, and the resistivity of that earth, are those formulated by Carson[2] and others; they are identical for both the self- and mutual impedances.

The suggestion for resolving out an internal impedance component which could be determined by laboratory scale measurements on short length samples of cable was made by R. G. McCurdy in 1926. Part of the measurements reported herewith were made in the following year.

Internal Impedance Data

Measurements of the internal impedance components have been made for 7 sizes of steel tape armored cables of the construction shown in Fig. 1, and, in addition, for cables enclosed in several sizes of wrought iron pipe. The method of measurement in either case was the same. (A similar method of measurement has been described recently by Zastrow and Wild.[3]) A voltage drop along a 20- to 100- t sample was measured by means of a fine insulated wire laid along the outer surface, the vector quotient of this voltage and the current in the sample representing the internal self-impedance. The voltage in a loop composed of the outside wire and a conductor inside the cable provided a measure of the internal mutual impedance, while the voltage drop along the inside of the sheath as measured by a core wire served to indicate the vector difference between the 2 impedances. Both voltages and currents were measured with an a-c potentiometer. All impedance values were corrected to a chosen base temperature of 70 deg F.

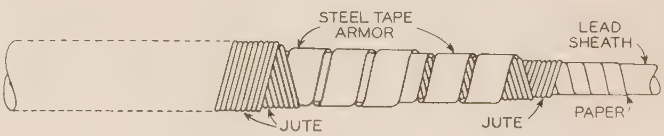


Fig. 1. Construction of steel tape armored telephone cable

Table I—Physical Dimensions, D-C Resistances, and Correlating Factors for Test Samples of Steel Tape Armored Cables

Sample No.	Dimensions: Lead Sheath		Dimensions: Steel Armor*					D-C Resistance at 70°F, Ohms Per 1,000 Ft		Correlating Factors: 25 Cycles		Correlating Factors: 60 Cycles	
	o.d., In.	t, Mils	ā, In.	t, Mils	b, In.	s, In.	α	Sheath	Sheath Plus Armor	k_x	k_r	k_x	k_r
1	2.63	125	1.54	61	2.0	0.45	14.7	0.108	0.102	1.51	1.15	3.62	2.76
2–4 (Avg)	2.63	125	1.49	43	2.0	0.42	15.0	0.108	0.103	1.12	0.87	2.69	2.07
5–7 (Avg)	2.38	125	1.33	44	2.0	0.45	17.0	0.118	0.110	1.22	0.91	2.93	2.19
8–9 (Avg)	2.38	125	1.37	42	1.25	0.33	10.6	0.118	0.112	1.17	0.90	2.80	2.15
10	1.75	125	1.07	43	1.75	0.44	19.1	0.165	0.145	1.43	1.01	3.43	2.44
11	1.56	155	1.02	43	1.75	0.44	20.1	0.155	0.135	1.48	1.04	3.56	2.50
12	1.38	125	0.90	40	1.25	0.38	16.7	0.205	0.175	1.56	1.09	3.74	2.63
13	1.22	125	0.73	40	1.25	0.31	20.0	0.245	0.215	1.94	1.37	4.66	3.29
14	0.85	75	0.55	42	1.25	0.28	26.5	0.525	0.395	2.48	1.61	5.95	3.86
15	0.47	70	0.31	19	0.75	0.095	25.6	1.110	0.905	2.32	1.68	5.58	4.02

Notes: Column headings are interpreted as follows: o.d., outside diameter; t, thickness; ā, mean radius of armor; b, tape width; s, air gap width; α, angle of lay measured to plane perpendicular to cable axis, in degrees.
Samples 2–4 are of the standard "full sized" dimensions.
For a discussion of the correlating factors and their use, see text (Internal Impedance Data).
* Two overlapped tapes of the indicated dimensions.

Complete physical dimensions of the steel tape armored cable samples are given in Table I together with the d-c resistances for both the lead sheath and the paralleled sheath and armor. The measured reactances and resistance loss increments for ranges of 25- and 60-cycle sheath currents are shown in Figs. 2 and 3. In these curves are presented the averages of the measured values for all sizes of cables armored with tapes of given thicknesses. The armor steel may be identified as having an initial d-c permeability of 250, a peak permeability of 1,500 at a field strength of 5 oersteds, and a resistivity of 12.9 μohm-cm. Although the steel employed in all of the samples was nominally the same, variations in its effective anneal were prominent. Hence, a more typical value for the impedance of a given cable may be expected from the composite representation than would be available from data on an individual sample.

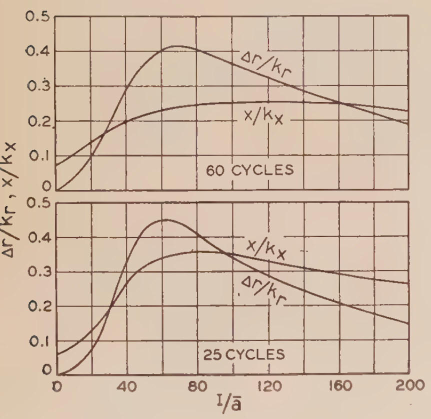


Fig. 2. Internal impedance components for steel tape armored telephone cables—composite chart for cables with tapes 40 mils thick

Ordinates × k_r or k_x from Table I give components in ohms per thousand feet. Abscissas × $\bar{a}$ (mean radius of armor) in inches give sheath currents in amperes

The reduction of the impedance data on cables of different sizes to permit their combined presentation is based upon the following considerations: For a given sheath current (the armor is assumed, as is nearly enough the case, to carry no current) the magnetic field strength within the armor of a given size of cable is inversely proportional to the mean radius ($\bar{a}$) of the armor. Hence the parameter $I/\bar{a}$ may be employed to correlate conditions of equal magnetizing forces for the several cable sizes, and also the conditions for equal permeability if the μ-H characteristics for the respective steel armorings are the same. Since the internal reactance and loss resistance are determined by the permeability and the physical dimensions of the armor, it remains only to weight the differing dimensions properly in order to provide a common relationship in terms of $I/\bar{a}$. Such weighting is accomplished by the division of the impedance components observed for each size of cable by the corresponding "correlating factors" of Table I. Thus, in Figs. 2 and 3 are plotted the quotients x/k_x, $\Delta r/kr$ versus $I/\bar{a}$. To determine the components x, Δr for a particular size of cable at a given current requires only the multiplication by the proper constants from Table I.

The correlating factors, derived from considerations similar to those treated in items 4 and 5 of the bibliography, are as follows:

$$k_x = \frac{ntfb\cos^2\alpha}{(b+s)\bar{a}} \qquad k_r = \frac{ntf}{\bar{a}}\left(\frac{b\cos^2\alpha}{b+s}\right)^2 \tag{3}$$

Notations and units employed in the evaluations of Table I are:

n = number of armor tapes, numeric
t = thickness of armor tapes, mils
f = frequency, cycles per second
b = width of armor tapes, inches
s = width of air gap between tape turns, inches
α = angle of lay of tapes, degrees.

Although frequency and tape thickness appear in this formulation, the failure to consider the influence of eddy current screening limits the application to fixed values of these variables. Changes in dimensions other than tape thickness are accounted for completely, however, so that by computation of the proper correlating factors the curves of Figs. 2 and 3 may be used to predict the impedance values for cables other than those listed in Table I.

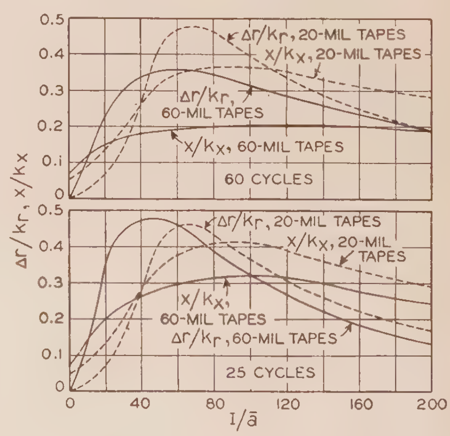
For cables armored with spirally wrapped tapes, the cross section, resistivity, and effective length of the tapes compared with those of the lead sheath make the armor currents unimportant. The validity of the foregoing considerations is dependent upon this condition. Under the same condition, the internal impedance components are the same for the self-impedance of the sheath and the mutual impedance between the sheath and the cable conductors, as was verified by the measurements. The internal impedances are, therefore:

$$z_{22} = r_{22} + \Delta r + jx \qquad z_{23} = \Delta r + jx \tag{4}$$

where r_{22} is the d-c resistance of the sheath or paralleled sheath and armor.

With cables installed in iron pipe conduit, a major fraction of the current is carried by the pipe, skin effect is prominent, and a more complicated picture results. Presentation of the data for each individual construction is required, and the different flux linkages constituting the self- and mutual impedances

Fig. 3. Internal impedance components for steel tape armored telephone cables—composite chart or cables with tapes 20 and 60 mils thick



Ordinates × k_r or k_x from Table I give components in ohms per thousand feet. Abscissas × $\bar{a}$ (mean radius of armor) in inches give sheath currents in amperes

demand separate consideration. Figure 4 indicates the internal self-impedance for the combination, in parallel, of a full-sized lead sheath ($2^5/_8$-in. outer diameter, $^1/_8$-in. walls) and an enclosing wrought iron pipe (nominal size $3^1/_2$-in. inner diameter, $^1/_4$-in. walls); also, the difference or "leakage" impedance, $z_{22}-z_{23}$.

Harmonic Frequencies. Since in the range of harmonics of 25- and 60-cycle fundamentals the shielding against magnetic induction afforded by an ordinary lead sheath usually is sufficient to meet practical needs, the improvement afforded by iron seldom will be required. Furthermore, the gain from the armor is by no means as large at the higher frequencies. Hence, although extensive impedance data have been obtained for the voice frequency range, they will not be presented.

Another aspect of the higher frequency problem is the matter of harmonic generation by iron armor or pipe conduit. A thorough experimental study of this effect has demonstrated that there is little possibility of serious voice frequency interference from such cause.

Practical Computations

The initial step in any shielding computation is the determination of the unshielded value of the longitudinal disturbing voltage at the position of the disturbed conductor. The magnitude of this electric field is formulated as the product of the disturbing or fault current and the mutual impedance between the disturbing and disturbed circuits;[6] upon its value and the self-impedance of the grounded cable sheath depend the magnitude and phase of the induced shielding current. However, since the impedance of an iron-surrounded sheath varies with the current carried, it is necessary to solve the analytical expression for that current by successive approximations from the experimental impedance-current relations. Thence, the determination of the shield factor and, finally, the resultant or shielded voltage is straightforward. Computations for aërial and underground cables differ only in the analytical expressions required to represent the sheath current: in one case, for an essentially insulated conductor with definite grounding connections; in the other, for a continuously leaky conductor.

Aërial Armored Cables. For an aërial cable with ground connections only at the ends of an exposure or at points beyond, separated by a length l, the relations of the introductory discussion are directly applicable. The sheath current is given by:

$$I_2 = -\frac{E_3}{Z_{22}} = -\frac{E_3}{z_{22} + Z^{\circ}_{22} + R/l} \tag{5}$$

where z_{22} and Z°_{22} represent, respectively, the internal and external components of the self-impedance of the armored sheath per unit of length, and R the sum of the ground connection resistances. Computation of the external impedance component is discussed in reference 6 of the bibliography. Rough figures, assuming average values of earth resistivity, cable size, and elevation above ground, are $0.01 + j0.11$ at 25 cycles and $0.02 + j0.25$ at 60 cycles, both expressed in ohms per thousand feet.

In irregular exposures where the mutual impedance per unit of length is not constant, the total disturbing field is to be computed and divided by the exposure length to yield an average field value per unit of length, $\bar{E}_3$.

The laborious solution of eq. 5 by successive approximations may be avoided by computing, for a series of arbitrary values of I_2, and for several values of R/l, the disturbing fields that would produce such currents ($E_3 = -I_2Z_{22}$). In these computations the appropriate values of z_{22} are chosen from Fig. 2 or 3 and Table I. For the same ranges of I_2 and R/l

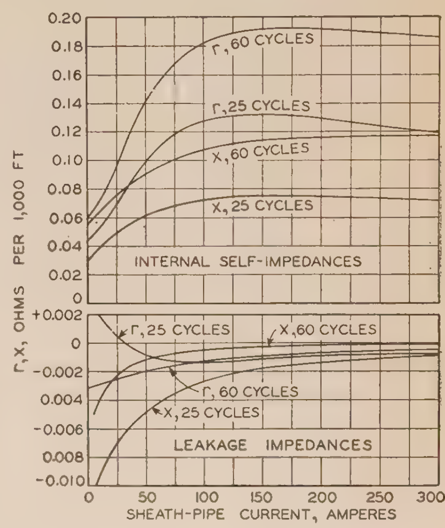


Fig. 4. Internal self- and leakage impedances for a full sized lead cable sheath enclosed in a $3^1/_2$-in. wrought iron pipe conduit

preliminary computations also should be made for the shield factor, which is simply:

$$\eta = 1 - \frac{Z_{23}}{Z_{22}} = \frac{Z_{22} - Z_{23}}{Z_{22}} = \frac{r_{22} + R/l}{z_{22} + Z^{\circ}_{22} + R/l} \tag{6}$$

since $Z^{\circ}_{22} = Z^{\circ}_{23}$ and $z_{22} - z_{23} = r_{22}$. Thereafter from the plotted results of these 2 sets of computations (I_2 vs. E_3, η vs. I_2, both as families in R/l) may be found the shield factor obtaining under the conditions of a given problem.

Figures 5 and 6, representing the shield factors for full-sized tape-armored cable sheaths as functions of the disturbing field strength and the d-c resistance of the sheath and its grounds, were prepared by an elaboration of the foregoing process. Presented as contour diagrams, these charts permit the direct reading of a shield factor from the indexed contour line passing through or nearest to the intersection of the appropriate values of the coördinates E_3 and $R/l + r_{22}$. The inclusion of the d-c resistance of the sheath in the latter variable renders the charts applicable to sheaths with added conductivity, great improvements in the shielding being possible from the paralleling of unused core conductors or specially provided copper within the sheath.

A heavy ordinate drawn at the value $R/l + r_{22} = 0.103$ represents the case of a standard full-sized cable with perfect ground connections. In Fig. 5, which shows the shield factors for 60-cycle induction, it may be observed, upon following this ordinate through the range of field values, that the factor

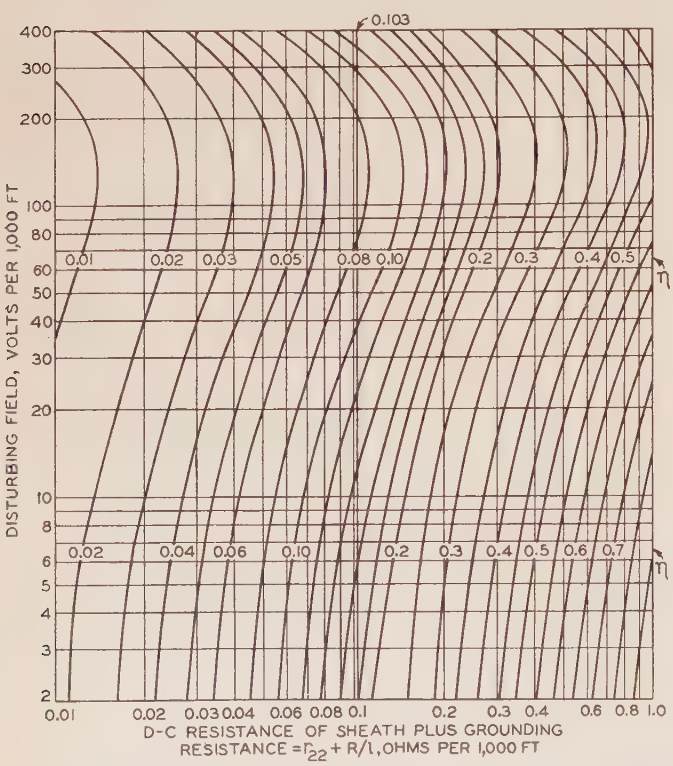
decreases from 0.18 to 0.08 and then increases. The corresponding range for 25 cycles, as read from Fig. 6, is 0.36 to 0.14. These may be compared with the factors for an unarmored cable sheath, otherwise identical, of 0.44 and 0.72 for the 2 frequencies. Since the latter are independent of field strength, the advantage of the armored sheath in the more severe exposures is particularly striking. Although it is not possible to set a figure for an "average" disturbing field, it may be stated that an exposure in which the field would exceed that for optimum shielding would be considered most severe.

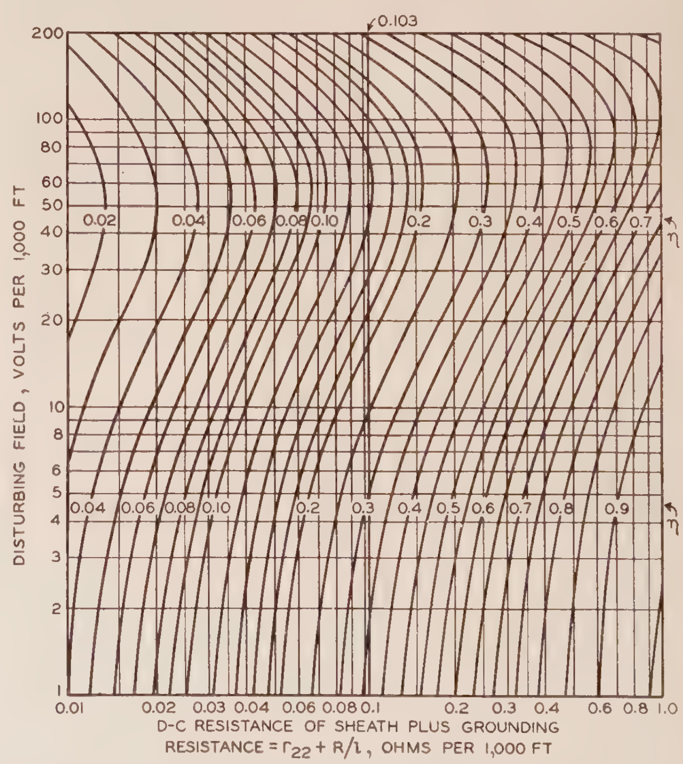
The shield factors for any of the smaller 40-mil tape armored cables listed in Table I are approximately the same, throughout the range of disturbing field values, as those for the full sized cable, perfect ground connections being assumed in either case. This is due to an increase in the internal impedance components resulting from the placement of the armor nearer the axis of the cable, which nearly compensates for the adverse effect of the higher sheath resistance. With less than perfect grounding, the shield factors for the smaller cables may be even lower than the corresponding figures for the full sized cable.

Underground Cables. By reason of their continuous contact with the earth, underground cable sheaths ordinarily do not require additional grounding to afford effective shielding. This is particularly true if the cable length exceeds that of the exposure by even moderate distances. In fact, in the latter instance, the shield factor applying to the voltage for the entire cable length approaches that obtained when the sheath is perfectly grounded at the exposure terminals.

Computation of the shield factors for an underground cable sheath is complicated by the fact that the shielding current is not constant along the extent of the cable, a difficulty that can be avoided only by consideration of average current values. To determine the latter, recourse must be had to the classical transmission equations for a continuously leaky line. Figures 7 and 8, representing the shield factors for buried full-sized tape-armored cables, exposed to 60- and 25-cycle induction, were prepared on that basis. Instead of the parameter R/l applied in the case of aërial cables, there appears the quantity $l\sqrt{G}$, in which l is the exposure length and G the shunt conductance or "leakance" of sheath to earth, per unit of length. The shield factors given include the additional reductions within moderate-length extensions by which the cable is assumed to overlap the actual exposure.

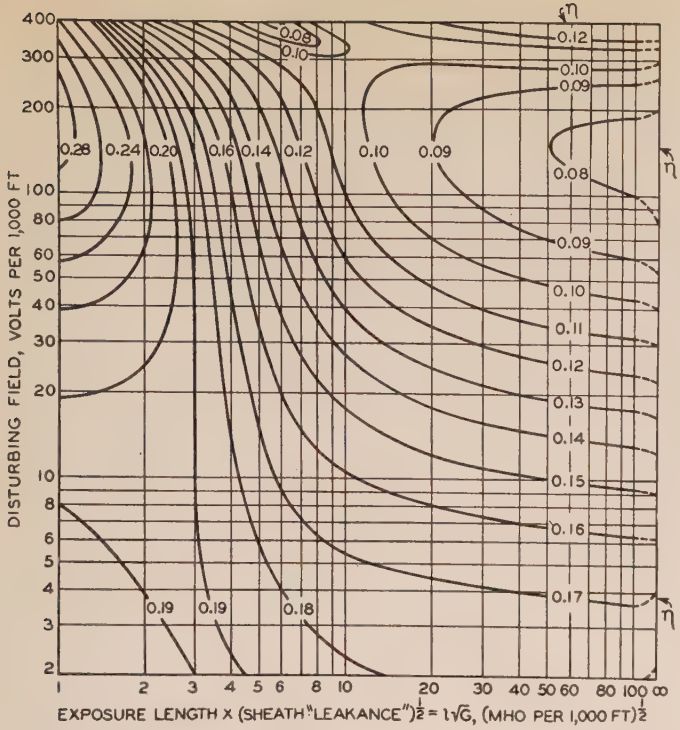
Although the "leakance" depends upon the nature and moisture content of the soil in which the cable is installed, the variation is not so wide as might be expected. Measurements of the "leakance" for full sized armored cables installed under widely different conditions have indicated a range of from 0.5 to 3 mhos per thousand feet, a value of 1 to 2 mhos being common. Hence, even with relatively short exposures, the product $l\sqrt{G}$ may attain values of 10 or more, for which the shield factors do not differ greatly from those for an infinite value. Since for the latter condition, the factors are the same as those for a cable provided with perfect grounds at the ends of an exposure, it is apparent that the simpler computational methods of the preceding section often will apply (R/l being set equal to 0).

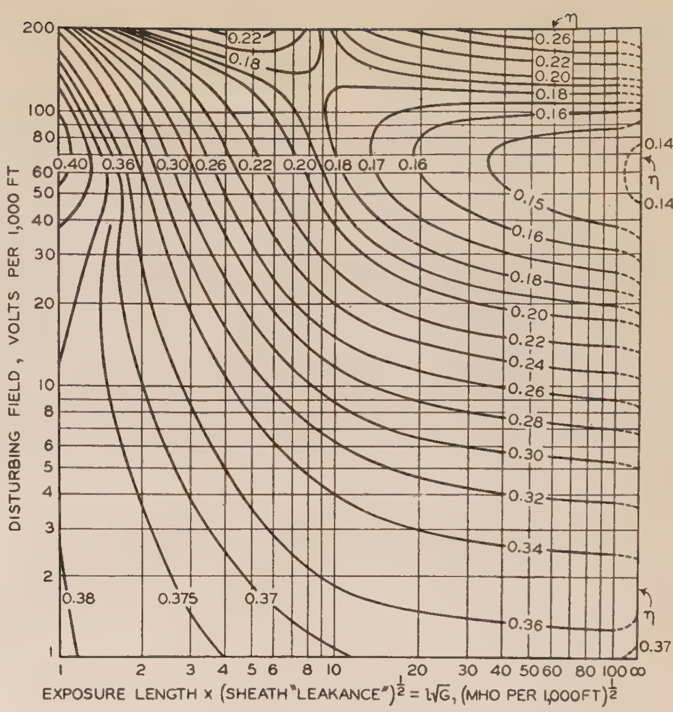




Figs. 5 and 6. Contour diagrams of 60-cycle (left) and 25-cycle (right) shield factors η for full sized steel tape armored telephone cable sheath, aerial

Grounding connections located at ends of exposure or beyond





Figs. 7 and 8. Contour diagrams of 60-cycle (left) and 25-cycle (right) shield factors η for full sized steel tape armored telephone cable sheath, underground

The cable is assumed to extend for moderate distances beyond the ends of the exposure; the added shielding within these extensions is included

Shield factors for cables installed in iron pipe conduit may be computed by this simplified method, the "leakance" being of even higher value than that for armored cable, and the derived shield factors of such low order as to minimize the need for more accurate evaluation (60-cycle factors of less than 0.01 are attainable). For this application:

$$\eta = \frac{z_{22} - z_{23}}{z_{22} + Z^{\circ}_{22}} \qquad (7)$$

in which the numerator is the leakage impedance given in Fig. 4. The external impedance, Z°_{22}, differs but little from that for a cable at the surface of the earth.[6]

Realization of the full shielding benefits of iron pipe conduit is dependent largely upon the maintenance of the electrical continuity of the pipe, both throughout the exposure and for at least short distances beyond. This necessitates welding the pipe joints and bonding around manholes.

Corrosion of an iron pipe conduit in service, if serious, would diminish the shielding benefits to a far greater extent than would similar damage to iron tape armoring which serves principally as a magnetic loading and not as a current carrying sheath.

Voltages From Sheath to Ground. Adequate grounding and complete continuity of a cable sheath passing through a severe inductive exposure are important not only for the more effective shielding of the communication circuits, but also as insurance against excessive voltages between the sheath itself and ground. Voltages from an iron-surrounded cable sheath to ground are less, under comparable conditions, than those for a plain lead-sheathed cable.

Field Observations

Two extensive field studies have been made of the shielding afforded by iron-surrounded cable sheaths. In the first of these, a 6,000-ft length of the Richmond-Petersburg (Va.) telephone toll cable was installed in an iron pipe conduit (full sized cable, 3-in. wrought iron pipe) and measurements were made

Table II—Comparison of Observed and Predicted Shield Factors

	Cable	Frequency, Cycles Per Sec	Disturbing Field Volts Per 1,000 Ft	Shield Factors Observed	Shield Factors Predicted
Richmond, Va.	Full sized cable installed in 3-in. wrought iron pipe conduit	25	1.4	0.06	0.05
		60	2.7	0.009	0.008
Cisco, Texas	Full sized steel tape armored cable	60	1.4	0.18	0.18
			4.9	0.16	0.17

of the voltages induced by a paralleling ground return circuit carrying currents of various magnitudes at frequencies between 15 and 2,000 cycles. In the second, like measurements were made, at 60 cycles only, for a 12,000-ft experimental exposure on the Fort Worth-Cisco (Texas) toll cable, all of which (110 miles) was of iron tape armored construction.[7] These field studies were made possible through the extensive coöperation of engineers of the Chesapeake and Potomac and the Southwestern Bell Telephone companies.

Although it is impossible to present more than a

few items from the test results, the entries in Table II indicate the order of agreement obtained between observed and computed shield factors.

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Energy Consumption of Multiple Unit Cars

In this article are analyzed the effects of increasing the rate of acceleration, free running speed, and rate of braking upon the energy consumption of multiple unit electric passenger cars. Analyses of 4 typical one-mile runs are given.

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RELATION between energy consumption and schedule speed of electrically propelled trains for various operating conditions has been widely discussed, and the results are known to most electric railroad operators interested in either urban or interurban transportation. The object of this article is to show where energy can be saved by increasing the rate of acceleration, free running speed, and rate of braking, or by any one of these changes in operating conditions, keeping the schedule speed and length of run the same. By analyzing the distribution of the total energy input to a car it is not difficult to determine the greatest possibilities of energy saving.

Written especially for ELECTRICAL ENGINEERING. *Not published in pamphlet form.*

Calculations from which the data given were obtained are based upon a modern 3000-volt d-c multiple-unit car equipment, operated by the Delaware, Lackawanna and Western Railroad. Speed-time curve calculations have been made on the basis of the following assumptions: an average line potential of 2,700 volts; level tangent track; acceleration and braking, 1.5 mph per second; a 4-car train, 70 tons per car, using the same gearing and wheel diameter as were furnished with the equipment (the gear reduction on the traction motors is 2.68 and the wheel diameter is 36.5 in.).

To understand clearly the distribution of energy, a typical run will be followed through. Starting with the input to the train (during the time of power on) part of the energy goes to the auxiliaries and part supplies the losses in the resistors; part goes to supply the traction motor losses, while the part that becomes the output of the traction motors is converted principally into kinetic energy; the remainder is used to overcome the train friction. This process continues until power is shut off for coasting. The instant power is off, no more energy can be supplied to the traction motors; hence, the kinetic energy stored in the train by virtue of its velocity is used to overcome the train friction for the remainder of the run. However, only a small part of this kinetic energy is used for work; the larger part becomes a braking loss.

From the following formulas the kinetic energy of the train and the work done can be calculated:

$$\text{Kinetic energy} = \frac{(wv^2)}{(2g)} \times 3.766 \times 10^{-7} \text{ kwhr}$$

$$\text{Work done} = Fs \times 3.766 \times 10^{-7} \text{ kwhr}$$

where

w = weight of train in pounds (increased by 9 per cent for rotational element)
v = velocity of train in feet per second
s = distance in feet
F = pounds friction of train

For an example of energy distribution, a one-mile run will be analyzed including 10-sec coasting and a 25-sec stop, giving a schedule speed of 26 mph. A speed-time curve and an energy consumption diagram for such a run are shown in Fig. 1. Power is applied until the train attains a speed of 47.1 mph

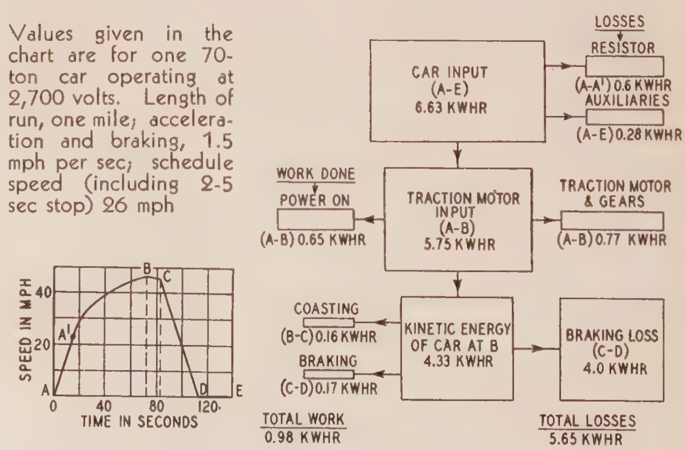

Fig. 1. Energy distribution chart and speed-time curve for run No. 1

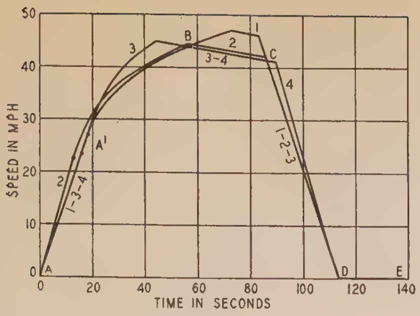

Fig. 2. Comparison of speed-time curves for the 4 runs analyzed

Schedule speed of all runs (including 25-sec stop) 26 mph

at B and has traveled 3,553 ft; the train then coasts from B to C for 10 sec, covering a distance of 685 ft and slowing down to 46.2 mph. At C the brakes are applied and the train stops at D, the distance of braking being 1,042 ft.

During the run A to E 6.63 kwhr of energy per car is taken from the trolley; 0.6 kwhr is consumed by the resistors during acceleration (A to A^1) and 0.28 kwhr is used by the auxiliaries (A to E, dynamotor and compressor). This leaves 5.75 kwhr input to traction motors (A to B). For the time power is on (A to B) 0.77 kwhr is consumed by the traction motor and gear losses, leaving 4.98 kwhr output available for work. During this time the train has traveled 3,553 ft, which requires only 0.65 kwhr of work per car. Therefore, at B 4.33 kwhr is stored up in each car as kinetic energy, and if the train were allowed to coast from C to a standstill then all this kinetic energy would be used to do work. The train coasts only from B to C, however, using 0.16 kwhr per car for work, so at C the kinetic energy of each car is 4.17 kwhr. From C to D the brakes are applied. The energy required to cover the distance from C to D is only 0.17 kwhr per car, but 4.17 kwhr is available at C; hence, 4 kwhr must be consumed by the brakes and, of course, is a loss.

Thus, from the energy distribution chart in Fig. 1 it may be seen that the total work done is 0.98 kwhr and the total losses are 5.65 kwhr per car. For a given schedule speed the work will remain practically constant, so that in order to decrease the energy consumption the total losses must be reduced. For a given time the energy consumed by the auxiliaries will remain constant. Hence, there are 3 items to consider, namely: (1) resistor losses, (2) traction motor and gear losses, and (3) braking losses. The braking loss is the largest and offers the greatest possibility for improvement. The only way the braking loss can be reduced is to brake at a lower speed, which means more coasting; and in order to maintain the same schedule speed a higher rate of acceleration, either initial or average, or a higher rate of braking must be used. In other words, any time lost in coasting to a lower speed must be made up during the time power is on or during the braking time.

To determine the effect of increasing the rate of acceleration and braking, analyses of the energy consumption for 3 different types of one-mile runs were made; the results are given in Table I, with corresponding speed-time curves shown in Fig. 2. For comparative purposes, the data of Fig. 1 and the

Table I—Analyses of Energy Consumption of One 70-Ton Car for 4 Typical One-Mile Runs

Run Number	1	2	3	4
Acceleration (mph per sec)	1.5	1.75	1.5	1.5
Braking (mph per sec)	1.5	1.5	1.5	1.75
Schedule speed (mph)	26	26	26	26
Gearing	59/22	59/22	56/25	59/22
Car input (kwhr)	6.63	5.85	6.14	5.74
Work done during "power on"	0.65	0.46	0.31	0.42
Work done during coasting	0.16	0.386	0.56	0.44
Work done during braking	0.17	0.134	0.13	0.11
Total work done (kwhr)	0.98	0.98	1.00	0.97
Resistor losses	0.60	0.55	0.79	0.60
Auxiliaries	0.28	0.28	0.28	0.28
Traction motor and gear losses	0.77	0.71	0.81	0.69
Braking loss	4.00	3.33	3.26	3.20
Total losses (kwhr)	5.65	4.87	5.14	4.77

speed-time curve of Fig. 1 (run No. 1 also are included in Table I and Fig. 2, respectively.

Run No. 2 is the same as No. 1, except for the initial rate of acceleration, which is 1.75 mph per second for run No. 2. A comparison of the data for run No. 2 with that for No. 1 reveals the following: Total car input 5.85 kwhr, a saving of 0.78 kwhr over run No. 1. The total work done is the same, hence 0.78 kwhr is saved in losses. The resistor loss is 0.05 kwhr less, and the traction motor and gear losses are 0.06 kwhr less. The speed of braking was reduced from 46.2 to 42 mph, hence the braking losses were reduced from 4.0 to 3.33 kwhr, which means a saving of 0.67 kwhr in braking loss.

Run No. 3 has the same initial rate of acceleration and braking, length of stop, and schedule speed as No. 1, but with the gear reduction being decreased to 2.24. The change in gear ratio is to give a higher free running speed, hence a higher average acceleration while the power is on. Comparing the data for run No. 3 with that for No. 1, the total car input is found to be 0.49 kwhr less for No. 3. The resistor losses for run No. 3 are 0.19 kwhr greater because a higher initial accelerating current had to be used for a longer time than in No. 1 in order to obtain an acceleration of 1.5 mph per second with the reduced gear reduction. Because of the higher current the traction motor losses are 0.94 kwhr greater in run No. 3, but the greatest loss of all, that of braking, is 0.74 kwhr less than in No. 1. Although the resistor and traction motor and gear losses increase with a higher speed gearing, there is a net saving in energy consumption on account of the lower speed of braking, which for run No. 3 was 41.6 mph.

Run No. 4 has the same schedule speed, length of stop, rate of acceleration, and gear reduction as in No. 1, but employs a rate of braking of 1.75 instead of 1.5 mph per second. Comparing the data for run No. 4 with that for No. 1, the resistor losses are the same, the traction motor and gear losses are 0.08 kwhr less for No. 4, and the braking loss is 0.8 kwhr less.

By analyzing in a similar manner the distribution of total energy input for other combinations of operating conditions, it is possible to determine the possibilities of energy saving for any given length of run and for any given schedule speed.

Better Instrument Springs

The characteristics and stability of performance of the control springs used in electrical measuring instruments are important factors in the accuracy of such instruments. Supplementing the slight amount of published information on this subject, the following article presents some of the manufacturing knowledge necessary for the production of instrument springs of high quality.

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McGraw-Hill Pub. Co., New York, N. Y. Formerly of the Westinghouse Elec. & Mfg. Co., Newark, N. J.

ELECTRICAL measuring instruments play an important part in the development and testing of electrical machinery, in the operation and control of electrical equipment, and in the distribution and metering of electrical energy. In these applications of spring controlled instruments, the accuracy depends as much upon the performance and stability of the control springs as on the design of the torque producing elements. Such factors as jewels, pivots, permanent magnets, electrical design and the structure of the mechanism are well covered in the technical literature. However, the standard references on instruments, both in this country and abroad, cover only the usual data on the mechanics of spring design, and do not include the knowledge necessary to produce instrument springs of the high quality and performance required in modern sensitive instruments.

There are 2 unstable effects found in the application of spiral springs to electrical instruments: aging and hereditary hysteresis. Aging results in a slow permanent change in the zero position and calibration of the instrument over long periods of time. Hereditary hysteresis results in a time lag of the deflection in relation to the applied torque. Hysteresis is a temporary effect evidenced by the failure of the spring to return exactly to the zero position after having been deflected for a long period of time.

Information is needed regarding the effect on the performance of spiral springs of such factors as composition, mechanical condition of the spring material, rolling practice, forming methods, stabilizing heat treatments, design details, residual stresses, service conditions, and temperature. The present article includes information drawn from the results of several years of practical research on instrument springs and spring materials. While the information in this article might have been known in equivalent form by certain manufacturers of instrument springs, it has never been published so far as known to the author. Torsional pendulum tests, hardness tests, various forming and stabilizing heat treatments, spiral spring uncoiling tests, and measurements of hereditary hysteresis with the grid glow micrometer were used to obtain this information.

Essentially full text of a paper (No. 33-89) presented at the A.I.E.E. summer convention, Chicago, Ill., June 26–30, 1933.

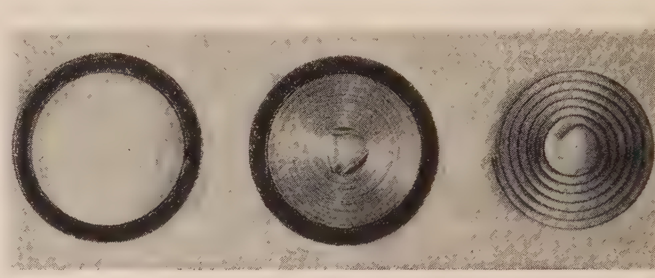
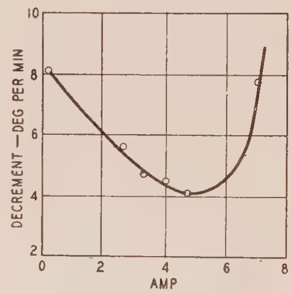


Fig. 1. Forming instrument springs. On the left is shown the forming barrel, in the middle is the barrel filled with spring ribbon ready for forming, and on the right is shown the formed spiral spring



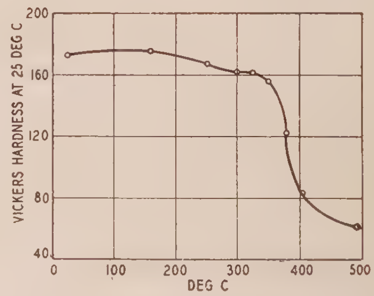


Fig. 2 (left). Effect of moderate heat treatment on the decrement of spring material in the torsional pendulum test. A current of 6 amp caused softening

Fig. 3 (right). Effect of forming temperature on the hardness of spring ribbon. The forming time was 15 min

Manufacture of Spiral Springs

In the usual shop method of making spiral instrument springs, hard drawn wire of a suitable material such as phosphor bronze is used. The degree of hardness or temper is measured usually by the amount that the cross section is reduced in cold drawing. This may be expressed by the number of wire sizes or the percentage cold reduction in area. For example, an annealed wire 0.064 in. diam drawn without further annealing to 0.010 in. diam is 16 numbers hard, or 97.5 per cent cold reduction in area.

The hard spring wire is rolled with several passes through the rolls to a hard, thin ribbon. Several

lengths of the ribbon are wound together around an arbor, and held tightly wound with a close-fitting barrel as illustrated in Fig. 1. The ribbons in the barrel then are formed into a spiral shape by heating the assembly for several minutes at a moderate temperature, in some instances at 300 deg C. When the ribbons are removed from the barrel they retain an approximation of the spiral shape they assumed when wound in the barrel.

The stresses set up in the ribbons when they are wound into the forming barrel are very high. As the ribbons in the barrel are heated the elastic strength of the material decreases. At the forming temperature the elastic strength is but a small fraction of its value at room temperature, and the springs set to the form in which they are constrained in the barrel. However, the high stresses set up in winding the ribbons into the barrel are not completely relieved by the heat treatment, since the material retains some elastic strength at any temperature below the annealing or softening point. Proof of the presence of residual stresses in the ribbon is found in the fact that the springs expand when they are removed from the forming barrel.

Effect of Heat Treatment on Hysteresis

In the torsional pendulum tests a rotating pendulum was suspended by a 20-in. length of spring wire.

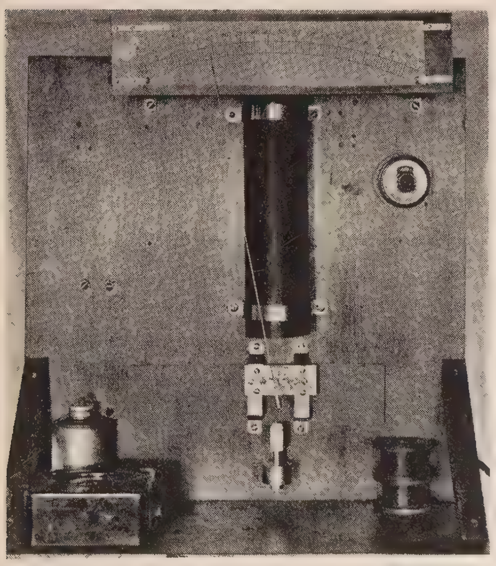


Fig. 4. Oven used in softening tests on spring wire

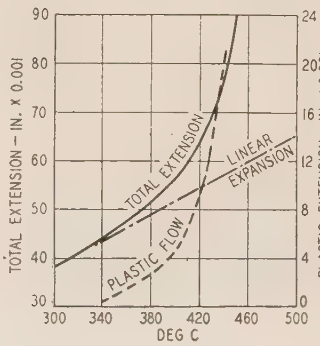
The maximum combined fiber stress at an amplitude of 100 deg was approximately 9,000 lb per sq in. with a wire diameter of 0.010 in. The wire was heat treated under the tension load of the pendulum weight by passing a current through the wire. The decrement of the torsional oscillations was measured after heat treatments at successively higher temperatures. In a typical test, shown in Fig. 2, a 2 per cent tin phosphor bronze wire with 45 per cent cold reduction in area was used. In this test the decrement or the hereditary hysteresis decreased rapidly as the heat treating temperature approached the softening point, as shown by the curve. In a series of tests using wires of various compositions and varying amounts of cold reduction in area similar results were obtained, with the exception that the effects were greater in wires with more cold working.

Hardness Tests

Phosphor bronze ribbons with varying amounts of cold reduction in area were subjected to successively higher temperatures, and the effect of this thermal treatment on the hardness of the strips was measured with a Vickers pyramid hardness tester. Large variations in the range of cold reduction in area did not produce corresponding variations in hardness. However, the softening range was found to be very critical as shown in Fig. 3 for a 2 per cent tin phosphor bronze ribbon, 0.015 in. thick and 0.165 in. wide, with 85 per cent cold reduction in area. Heat treating temperatures up to 350 deg C had little effect, but slightly higher temperatures caused a large decrease in hardness. A similar effect was found in all cold worked ribbons, but the initial hardness was not quite as high for lower amounts of cold working.

Softening Tests

One-foot lengths of phosphor bronze wire were heated in the small electric oven illustrated in Fig. 4, while under a constant tension load produced by a weight. The wire was clamped at the upper end of the oven and was passed between a pair of small rollers at the lower end. The rollers were held in contact with the wire by light spring pressure. Extension of the part of the specimen inside the oven was indicated by a pointer rotated by one of the rollers. When the wire was heated the pointer indicated the extension caused by thermal expansion. However, at elevated temperatures the tension load



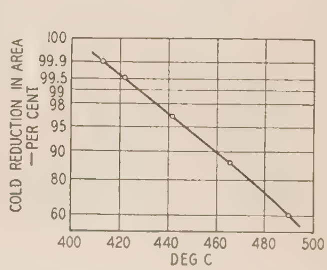


Fig. 5 (left). Softening test of spring wire

Fig. 6 (right). Effect of cold working on the softening temperature of spring wire

introduced permanent creep or plastic extension in addition to the thermal expansion effect. The test was performed by heating the oven at a uniform rate and measuring the temperature and total extension of the specimen. The plastic extension was obtained graphically by subtracting the calculated

temperature expansion from the total extension as shown in Fig. 5 for a typical test. The specimen illustrated was a 2 per cent tin phosphor bronze wire 0.010 in. in diameter, 12 in. long, with 97 per cent cold reduction in area. The tension load was 8,000 lb per sq in. and the heating rate was 35 deg C per minute. In this test there was no plastic extension until a temperature of approximately 330 deg C was reached. As the temperature was further increased the plastic extension increased very rapidly. The occurrence of plastic extension indicated that the material lost strength as the temperature was raised through 330 deg C.

Increased cold working in the spring material was found to lower the temperature at which the loss of strength or plastic extension occurred. The temperature at which the plastic extension reached 0.020 in. was determined for a series of specimens with varying amounts of cold reduction in area. In Fig. 6 it is shown that this temperature fell rapidly as the cold reduction in area was increased. Although this test method is not subject to rigorous interpretation, it demonstrates that the softening temperature of phosphor bronze spring wire is controlled by the amount of cold working in the material.

Effect of Temperature and Time on Forming

The effect of forming temperature and the time at temperature was investigated using a group of springs made from a spring ribbon prepared for a typical instrument spring. The spring material used was a commercial cold drawn 5 per cent tin phosphor bronze wire 0.008 in. in diameter. The ribbon was rolled in 8 passes to a cross section of 0.0022 in. by 0.023 in. The forming barrel, similar in shape to that shown in Fig. 1, had an inside diameter of 0.436 in. and accommodated 6 lengths of ribbon 9.5 in. long. The spring torque was 0.27 cm-g per revolution. Barrels filled with spring ribbon were formed at various temperatures from 250 to 320 deg C for 15 min. Other barrels were formed at 300 deg C for various lengths of time from 1 to 30 min. When the spiral springs were removed from the barrels, the springs expanded so that the outside diameter of the spring was larger than the inside diameter of the forming barrel. There was less increase in diameter of the spring when the temperature of forming approached the softening point, as shown in Fig. 8. The time at temperature also affected the amount of expansion. In Fig. 9 it is shown that a minimum time of 20 min at the forming temperature was required to complete the forming process.

The expansion of the spring as it was removed from the barrel provided a very useful method for determining the proper temperature and time for forming any given spring. In addition, the amount of expansion indicated the relative intensity of the residual stresses in the spiral spring.

Uncoiling Tests

When formed spiral springs are heated they show a tendency to uncoil. This uncoiling tendency was measured by heating the springs formed for 15 min

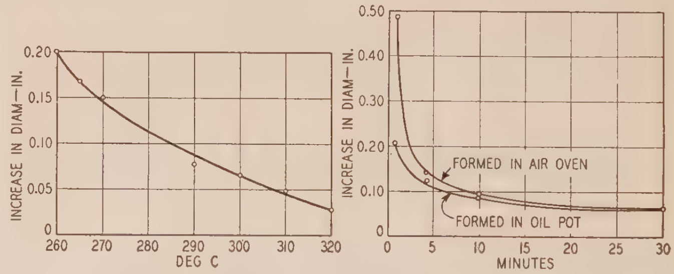
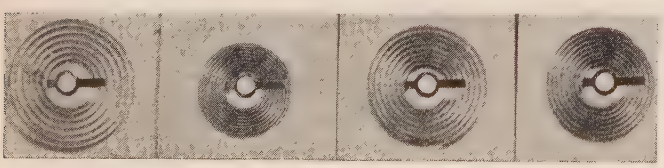


Fig. 8 (left). Effect of forming temperature on the outside diameter of spiral springs formed in the same barrel. Same springs as described in Fig. 7

Fig. 9 (right). Effect of forming time on the outside diameter of spiral springs formed in the same barrel. Same springs as described in Fig. 7. Formed at 300 deg C for 15 min

at 300 deg C to various temperatures. The rate of uncoiling is shown in Fig. 10 to increase very rapidly with only moderate increases in temperature. At 100 deg C the uncoiling rate was nearly 10,000 times as rapid as the rate at 35 deg C. The uncoiling at any constant temperature was found to proceed at a decreasing rate asymptotic to some final value, and the final amount of uncoiling was found to be larger with springs formed at lower temperatures. Measurements of the elastic modulus of the springs (torque per revolution) showed that the uncoiling was accompanied by an increase in the elastic modulus. The effect of forming temperature on the amount of uncoiling and change in elastic modulus is illustrated in Fig. 11. Springs formed at 260 deg C were subject to 3 times as much change as springs formed at 310 deg C. Tests on the springs formed at 300 to 320 deg C disclosed that the small initial uncoiling tendency was removed completely by heating the finished springs for 24 hr at 100 deg C. A small amount of uncoiling took place during this heat treatment, but there was no subsequent un-



A *B* *C* *D*

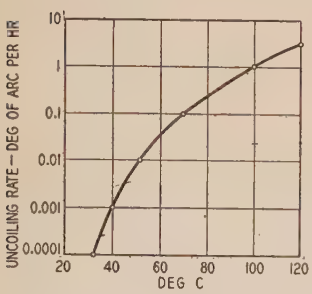
Fig. 7. Effect of forming temperature and forming time on the outside diameter of spiral springs formed in the same barrel

Springs *A* and *B* were fromed from identical ribbons in an air oven held at temperature for 15 min. Spring *A*, formed at 250 deg *C*, had an outside diameter of 0.633 in. Spring *B*, formed at 320 deg *C*, had an outside diameter of 0.461 in. Springs *C* and *D* were made from identical ribbons in an air oven held at 300 deg *C*. Spring *C*, formed for 4 min, had an outside diameter of 0.578 in. Spring *D*, formed for 30 min, had an outside diameter of 0.550 in.

coiling tendency at any lower temperature. Comparison of Fig. 8 and Fig. 11 shows that the uncoiling tendency, the aging tendency, and the expansion of the spring when removed from the barrel are all influenced in a similar manner by the forming temperature. This fact suggests that residual stresses are responsible for aging and uncoiling effects as well as the expansion effect in spiral springs.

Grid Glow Micrometer Tests

Hereditary hysteresis effects in spiral springs are very difficult to measure with precision. These



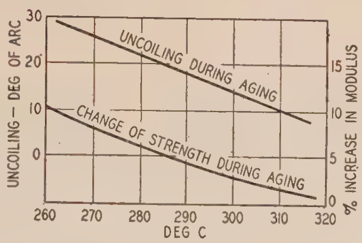


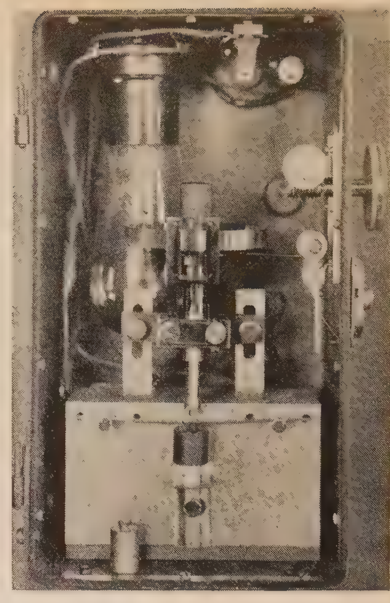
Fig. 10 (left). Effect of aging temperature on the rate of uncoiling of the spiral springs described in Fig. 7

Fig. 11 (right). Effect of forming temperature on uncoiling and increase in elastic modulus of spiral springs during aging. Same springs as described in Fig. 7. Aged at 100 deg C for 15 hrs

effects were investigated using flat strips of spring ribbon loaded in bending as illustrated in Fig. 12. A short length of ribbon was placed on 2 parallel horizontal pins and loaded with a weight hung midway between the pins. The deflection of the beam was measured with a micrometer head fitted with a sharp contact point. Contact between the micrometer point and the ribbon operated a grid glow tube to indicate the instant of contact. A large diameter drum and a magnifying lens was attached to the micrometer head to facilitate accurate readings; and a constant tension thread drive was used to make accurate settings of the micrometer. An autographic attachment was developed which produced a continuous record of displacements of the test specimen, so that a test could proceed without being disturbed. The grid glow micrometer was found to be sensitive to displacements of 0.00001 in. (ten millionths) with a contact circuit resistance of more than one megohm. With this apparatus precision measurements of hereditary hysteresis in instrument spring ribbon were made at low working stresses and over periods of time extending for several weeks.

Hereditary hysteresis in instrument spring ribbon was investigated under conditions of load and time similar to the service conditions of the instrument spring. The effect of heat treatment on hereditary hysteresis as obtained from the torsional pendulum test (Fig. 2) was confirmed. The continuous nature of the hysteresis effect is shown in Fig. 13 for a ribbon

Fig. 12. Grid glow micrometer used in hysteresis tests



of 5 per cent nickel bronze, 0.016 in. by 0.109 in., with 84 per cent cold reduction in area. The specimen was formed flat at 300 deg C for 15 min to relieve cold working stresses. At a maximum stress of 12,000 lb per sq in. the creep reached 0.28 per cent of the load deflection in 30 hr. After the load was removed recovery was approximately two-thirds completed in 30 hr. The recovery action was allowed to continue undisturbed for 7 days. When the recovery time was plotted to a logarithmic scale the recovery curve formed a straight line as shown by the right-hand curve of Fig. 13. Projection of the recovery curve to the point of complete re-

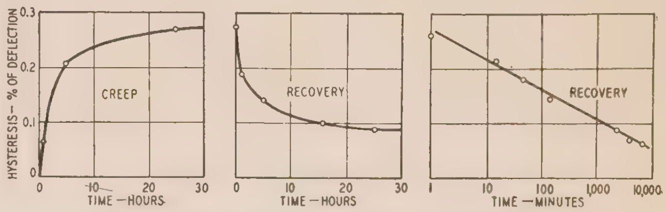


Fig. 13. Hereditary hysteresis in spring ribbon

covery gave a period of 42 days required to recover from the effects of a load sustained for 30 hr.

Conclusions

From these tests the following conclusions are drawn regarding the phosphor bronze spring materials used in the manufacture of spiral instrument springs:

1. Hereditary hysteresis is a minimum in instrument springs when the forming temperature is just below the softening point.

2. The softening temperature range for cold worked phosphor bronze spring material is very critical. Further, the softening temperature is lowered by an increase in the cold working of the material.

3. The increase in diameter of the spiral spring as it is removed from the forming barrel indicates the relative intensity of the residual stresses in the spring.

4. The tendency of the spiral spring to uncoil and increase in elastic modulus is a minimum under conditions that produce minimum

residual stresses. As in the case of hereditary hysteresis, forming at a temperature just below the softening point produces the minimum aging tendency.

5. The aging tendency of properly formed springs can be eliminated by low temperature heat treatment.

6. Hereditary hysteresis is of a progressively continuous nature, and the creep rate is more rapid than the subsequent recovery rate.

Springs made in accordance with the information presented in this article have been used in high grade indicating instruments with a marked improvement in performance. It is recognized that the details of the forming and aging process vary with the dimensions of the spring, and with the composition and mechanical condition of the spring material. However, the information given in this paper has been found to be sufficient for the development of manufacturing information for any of the usual instrument springs.

It is recognized that the work described in this article covers only one phase of the instrument spring problem. Additional information is needed on such subjects as the effect of composition, mechanical condition of the spring material, rolling practice, and temperature of loading on hereditary hysteresis and residual stresses. If some of the results presented here have been obtained by others but not reported a contributed discussion on the subject will be welcome.

Stray Load Loss Test on Induction Machines

A loading-back test has been used for the determination of the stray load losses in polyphase induction machines. This test, which was found to have a high degree of accuracy, enables the various losses to be separated. The application of the test is simple and convenient.

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THE experimental determination of the stray load losses in polyphase induction motors is a problem which still requires a satisfactory solution. In this paper is described a test, performed in the electrical engineering laboratory of Stanford University, which had for its object the establishment of a convenient and accurate method of determining these losses.

No discussion of the nature of stray load losses in induction machines will be given here as it is felt that this subject has already been covered by many excellent papers. Nor is it necessary to point out the desirability and need for a convenient method of arriving at an accurate determination of the amount of these losses by actual measurement. For the purposes of this paper it is sufficient to remember that these losses are a function of load current of the machine and that their magnitude is sufficiently great to warrant their inclusion in specified machine efficiency. Such being the case the designer requires the aid of dependable measurement of such losses.

The method employed for the determination of the stray load losses was essentially a loading-back test identical to that used with synchronous and continuous current machines. For the purpose of the tests 2 similar machines were connected by means of an ordinary belt drive in such a manner that one acting as a motor drove the other as a generator when connected to a common power line. Various degrees of loading were obtained by changing the pulley ratio, a few pulleys with slightly different diameters being used for this purpose.

The total losses of the combination were measured as power input to the system. The losses usually considered in calculating "conventional efficiency" and belt losses were subtracted from the total losses giving a value which is the sum of the stray load losses in both machines. This total stray load loss was plotted as a function of the arithmetical sum of the currents in the 2 machines and a simple method was developed for accurately proportioning the proper amount of the loss to its respective machine.

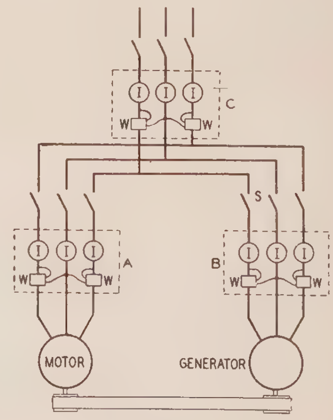


Fig. 1. Diagram of connections

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery. Manuscript submitted Nov. 24, 1932; released for publication Aug. 28, 1933. *Not published in pamphlet form.*

Certain minor incorrect assumptions which were made in the original calculations were investigated with the result that the errors caused by them were shown to be negligible.

The results of the test were compared with values obtained by a brake test and also by the "conventional method." While no refinements were employed in making the brake test the overall results from it and the loading-back test were in close agreement. The "conventional method" of course showed lower total losses and higher efficiency because of the omission of the stray load losses.

Three features of the test to be emphasized are:

1. Possibility of stray load loss determination in induction machines.
2. Separation of the various losses.
3. A high degree of accuracy.

Details of Method

The connection diagram of the machines showing the position of measuring instruments is given in Fig. 1. The input to the machine operated as a motor is measured by the instruments of group *A;* group *B* gives the output of the machine acting as a generator; and group *C* measures the losses in both machines and in the belt drive, all of which are supplied by the external circuit.

One of the important advantages of a loading-back test, in general, is the fact that losses are determined not as the difference between the input and output of a machine, but as a direct measurement. By the method used in this test the measurements of motor input and generator output are necessarily employed, and all the disadvantages of the input-output method would exist were not a correction applied to these measurements. To avoid completely any error which might arise from incorrect measurements of motor input and generator output a correction is applied to them so that their difference is exactly equal to the total power consumed by the losses as measured by the instruments of group *C* in Fig. 1. In other words, if the difference between the power readings in group *A* and group *B* meters is not equal to that of the group *C* meters the error thus determined is split equally between the motor and generator power readings. This completely eliminates the possibility of inaccuracy from the input and output readings as far as determination of losses is concerned.

The output of the motor is computed from its power input on the basis of "conventional efficiency" according to the rules of the A.I.E.E. Standards. This computed output is greater than the actual value by the stray load losses in the motor, i. e.:

$$W_c' - L_m = W_a' \tag{1}$$

where W_c' is the computed output of the motor, W_a' is the actual output of the motor, and L_m is the stray load losses in the motor.

Likewise the input into the generator is computed from its measured output. This gives a value of the input which is smaller than the actual by the amount of the stray load loss in the generator, i. e.:

$$W_c'' + L_g'' = W_a'' \tag{2}$$

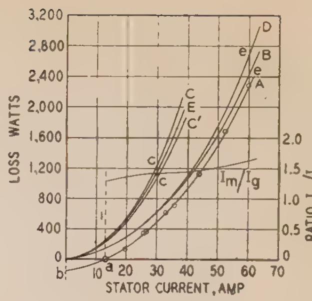


Fig. 2. Curves of stray load losses illustrating division between machines

where W_c'' is the computed value of the generator input, W_a'' is the actual value, and L_g is the stray load loss in the generator. The difference between W_a' and W_a'' is equal to the belt loss L_b, i. e.:

$$W_a' - W_a'' = L_b \tag{3}$$

Solving eq 1, 2, and 3 for $L_m = L_g$ there results:

$$(L_m + L_g) = W_c' - W_c'' - L_b$$

The problem is now reduced to the accurate division of the stray load losses between the 2 machines.

Division of the Stray Load Losses Between the Machines

Stray load losses in both machines, determined in the manner described above, are given on Fig. 2 (curve *A*) as a function of the arithmetical sum of the stator currents in both machines. Point *a* on the curve corresponds to the sum of the no-load currents in the 2 machines. According to the method of determining the iron loss the entire input to each machine acting separately as a motor at no load is classified as: stator copper loss, stator iron loss, and friction and windage loss, no part of the input being assigned to the stray load loss. Yet if the stray load loss is considered as a function of current, some of it must occur at no load due to the exciting current. This value of the stray loss at no load can be found by extrapolating curve *A* of Fig. 2 until it intersects the zero current ordinate (point *b*). Thus the amount 0-*b* previously classified as a part of iron loss should be properly referred to the stray load loss, which raises the stray loss curve into position *B*.

Division of the stray load loss may be accomplished by 2 methods: graphical and numerical.

Graphical Method

Denoting by $F(I_m + I_g)$ the experimental curve *B*, and by *k* the current ratio I_m/I_g (I_m being the motor current and I_g, the generator current), the problem can be stated analytically as follows:

$$F(I_m + I_g) = f(I_m) + f(I_g)$$

or:

$$F(I_g(1 + k)) = f(kI_g) + f(I_g) \tag{4}$$

also:

$$F(0) = 0; \text{ and } f(0) = 0$$

Here $f(I)$ is the required function, i. e., stray load loss in either machine in terms of the stator current. Though an analytical solution of eq 4 can be found in

terms of $F(I_m + I_g)$ and its derivatives (see Appendix), it is of little practical value because of its complexity. This is augmented by the fact that $F(I_m + I_g)$ is not readily obtainable from the experimental curve. In order to see how a graphical solution can be effected we shall note that the solution of eq 4 depends upon the value of k. We shall note, also, that values of k from zero to one cover the entire field in which the solution can exist, as all other values of k (outside of $0>k>1$) are merely reciprocals of those within this interval, and it does not matter which way we take the ratio of currents I_m/I_g as $f(I_m)$ and $f(I_g)$ are in fact one and the same function. Thus values of $k = 0$ and $k = 1$ give us the limiting values of $f(I)$. For $k = 0$, eq 4 gives:

$$F(I_g) = f(0) + f(I_g)$$

Since $f(0) = 0$, for this case the experimental curve B, Fig. 2, is the solution. The other limiting case is obtained for $k = 1$:

$$F(2I_g) = 2f(I_g)$$

Hence:

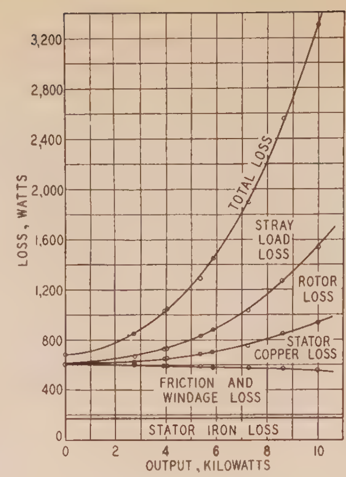
$$f(I_g) = {}^1/_2\, F(2I_g)$$

i. e., $f(I)$ can be obtained by plotting one-half of the ordinate of curve B against one-half of its abscissa. Curve C, Fig. 2, is obtained in this way. It represents the higher limit of the required function $f(I)$. We know now that the required function should lie within the 2 limits represented by curves B and C. To determine the location of $f(I)$ more accurately, curve C is used as the first approximation, and on the basis of this curve and the current ratio k (as determined from the I_m/I_g curve, plotted as a function of $I_m + I_g$), the curve of total stray loss in both machines is constructed (curve D). Naturally, as should be expected, the curve thus obtained lies above the experimental curve, which shows that a correction should be introduced into curve C. By taking the amount of error from curve E (*e. g.*: *e-e*), and subtracting one-half of it from curve C at half of the abscissa of curve D (*e. g.*: *c-c*) we obtain a second approximation for $f(I)$, which is slightly closer than C to the true location of $f(I)$, and lies below it (curve C'). If now we draw curve E exactly between curves C and C', we will be within draftsman's accuracy of the exact location of $f(I)$, as can be checked by reconstruction of the total stray load loss curve on the basis of curve E and I_m/I_g ratio.

Curves C' and D are drawn on Fig. 2 merely for the purpose of illustration. These curves are not at all necessary for the determination of curve E, as the process of determination of the error (*e. g.*: *e-e*) can be done numerically for a few values of abscissa $(I_m + I_g)$, and one-fourth of the error may be subtracted directly from C to obtain E.

Numerical Method

The shape of the stray load loss curve (curve E, Fig. 2) resembles that of a parabola of the second degree, which suggests a possibility of dividing the total stray load loss between the machines in proportion to the square of the current. An analysis of



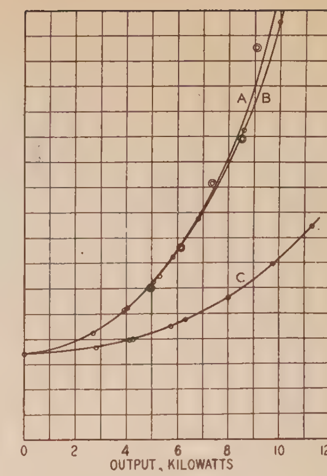


Fig. 3 (left). Separate losses in the motor as determined by the loading-back test

Fig. 4 (right). Comparison of total motor losses as determined by different methods

Curve A. Loss by brake test
Curve B. Loss by loading-back test
Curve C. Loss by conventional efficiency method

the curve shows that the latter does not satisfy exactly a simple equation of the form:

$$L = K I^n$$

where L is the stray load loss, I is the line current, and K and n are constants. Actually, both K and n vary as follows in the particular case of the machines used: for the lower part of the curve $K = 4.57$, $n = 1.525$; for the upper part $K = 1.21$, $n = 2.03$. Nevertheless, the division of the total stray load loss in proportion to the square of the current gives a fairly accurate result. The applicability of this method of stray load loss division for practical purposes can be determined by several tests of different types of motors.

Determination of Belt Loss

In order to determine the loss in the belt it may be assumed that it consists of 2 components: (1) loss due to the slip of the belt, which varies with the load, and can be determined from the expression:

$$\text{Belt slip loss} = \frac{\text{Motor output} \times \text{belt slip (rpm)}}{\text{Motor speed (rpm)}}$$

and: (2) the loss due to belt adhesion, internal friction, windage, increased bearing friction due to tension in the belt, etc. This group of belt losses is assumed to be constant, which is a fair assumption as the tension in the belt is the only factor affecting this loss that may change with load. This constant belt loss is determined for each load point by measuring the watts input to the motor with the generator belted to it, but not electrically connected. From the data obtained, the constant belt loss is found as the difference between the motor input and motor copper loss, stator iron loss, rotor loss, motor friction and windage loss, and the generator friction and windage loss. As the load on the motor is very small in this case, the conventional method of motor

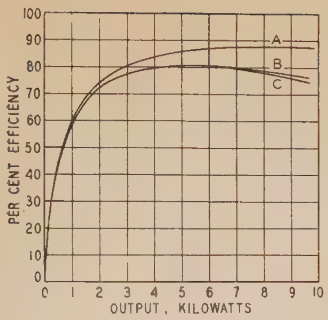


Fig. 5. Comparison of motor efficiencies determined by different methods

Curve *A*. Conventional efficiency

Curve *B*. Efficiency by loading-back test

Curve *C*. Efficiency by brake test

loss determination (as described in the A.I.E.E. Standards) gives a sufficiently accurate result. The loss due to the belt slip can be neglected; in fact, no belt slip could be detected with the generator not connected to the line.

The belt slip, necessary in order to compute the variable part of the belt loss, was determined from the actual pulley ratio, and the actual speed of the motor and the generator, which, in turn, was determined by means of a synchronously driven stroboscope.

Assumptions Investigated

In the initial computations by this method the motor rotor losses are calculated from the expression:

$$\text{Rotor loss} = \frac{\text{Stator output} \times \text{rotor slip (rpm)}}{\text{Synchronous speed (rpm)}}$$

in which the stator output is taken as the motor input less the sum of stator copper loss based upon its d-c resistance and the stator iron loss. That portion of the stray load losses which occurs in the stator is neglected in this calculation because it has not as yet been determined. This procedure gives a value for the rotor loss which is slightly higher than its true value. However, this error in the motor calculations is partly compensated for by the fact that the value of rotor loss used for the generator is too low, as a result of neglecting to add the stray load losses of this machine to its output in obtaining a value for the stator input.

Also, it has been indicated above that the belt slip loss may be slightly wrong due to a small error in the value used for the motor output employed in its calculation.

In order to obtain an idea of the magnitude of the error in the stray load losses resulting from the above approximations, after the stray load losses were computed the procedure of loss computation was repeated on the basis of ascribing all the stray load losses of each machine to its stator. New values of stray load losses thus obtained were practically identical with the previous values for all but very low currents where the difference was small enough to be negligible.

It is well to point out that there are 2 assumptions involved in the test which may impair its accuracy. One is that the stray load loss is the same function of current in each of the motors. Though one of the machines is operated as a motor, and the other as a generator, there is hardly any good reason to think that this assumption may cause any appreciable degree of inaccuracy. The other assumption is that the variable part of the belt loss is due only to the belt slip. This may not be quite correct, as the tension in the belt may change with the load, causing a change in the bearing friction. However, even if it does change somewhat, the error due to assuming it constant cannot be appreciable, as the total amount of the belt loss, which is assumed to be constant, is very small.

Results

Three previously mentioned features of the test should be emphasized: possibility of the stray load loss determination, separation of losses, and high degree of accuracy.

Losses in the machine operated as a motor are given in Fig. 3. The total loss in the machine is separated into 5 components: (1) the stator no-load loss, which includes all the tooth-frequency loss occurring at no-load; (2) the stator d-c copper loss; (3) the stray load losses in the stator and rotor; (4) fundamental frequency rotor loss; and (5) the friction and windage loss. The points indicated on the curves by small circles are the actual experimentally determined values. Good agreement between the experimental points and the smooth curves connecting them serves as one of the indications of the accuracy of the test.

In order to show more positively the real worth of the test, a brake test of the motor was made with no attempt at refinements. The comparative values of losses as determined by the brake, loading-back, and the conventional method is shown in Fig. 4 as a function of the kilowatt output of the motor. The comparative efficiencies of the motor, as determined by the 3 methods, are shown in Fig. 5. As the 2 graphs indicate, there is a good agreement between the results of the brake test and loading-back test, whereas the value of the conventional loss is too low.

The application of the loading-back test of various induction motors becomes very simple and convenient once the losses in one of the machines of the test have been accurately determined.

Emphasis should be placed upon the fact that this particular test was made on only one type of induction motor. Consequently the results obtained cannot be taken to indicate the amount of the various losses on induction motors in general. The test was made purely for the purpose of establishing the worth of this method of determining the values of the various losses in induction motors.

Appendix—Analytical Solution of the Division of the Stray Load Loss Between the 2 Motors

Statement of the Problem

Denoting the motor current by $I_m = x$, and the generator current by $I_g = y$, we have the following conditions:

$$F(x+y) = f(x) + f(y) \tag{5}$$

$$x = ky$$

$$F(0) = 0$$

$$f(0) = 0$$

k is known, being the ratio of currents in the 2 machines
$F(x + y)$ is known being the experimental curve B, Fig. 2
$f(x)$ or $f(y)$ is to be found

SOLUTION

Equation 5 can be written as:

$$F\big(y(1 + k)\big) = f(ky) + f(y)$$

Differentiating this expression with respect to y, taking k as a constant:

$$(1 + k)F'\big(y(1 + k)\big) = kf'(ky) + f'(y)$$

When $y = 0$, this gives:

$$(1 + k)F'(0) = (1 + k)f'(0)$$

i. e.:

$$F'(0) = f'(0),$$

because,

$$f'(ky) = f'(0) = f'(y)$$

Differentiating eq 5 twice with respect to y:

$$(1 + k)^2F''\big(y(1 + k)\big) = k^2f''(ky) + f''(y)$$

For $y = 0$, this gives:

$$(1 + k)^2F''(0) = (1 + k^2)f''(0)$$

Hence:

$$f''(0) = \frac{(1 + k)^2}{(1 + k^2)} F''(0)$$

Similarly:

$$f^{(n)}(0) = \frac{(1 + k)^n}{(1 + k^n)} F^{(n)}(0)$$

Expanding now $f(y)$ about $y = 0$. we have:

$$f(y) = f(0) + f'(0)y + f''(0)\frac{y^2}{1\cdot 2} + f'''(0)\frac{y^3}{1\cdot 2\cdot 3} + \ldots$$
$$= 0 + F'(0)y + \frac{(1 + k)^2F''(0)}{2!\,(1 + k^2)} y^2 + \ldots\ldots$$
$$+ \frac{(1 + k)^nF^{(n)}(0)}{n!\,(1 + k^n)} y^n + \ldots$$

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A Unique Oscillograph

An optical system designed to permit simultaneous viewing and photographing has been incorporated in a new portable oscillograph which is rugged in construction and weighs but 22 lb. It is particularly adapted for observing and photographing recurrent wave forms and certain types of transient phenomena. This oscillograph should find many fields of application where the refinements of present larger types are not required.

By
K. A. OPLINGER
ASSOCIATE A.I.E.E.

Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.

A NEW simplified, portable oscillograph has been developed which is comparable in size, simplicity, and ruggedness with the average electrical indicating instrument. The following outstanding features, most of them unique for a portable oscillograph of small size, are incorporated in this oscillograph:

1. Simultaneous viewing and photographing.

2. A continuous time axis furnished by a small revolving mirror the speed of which is variable.

3. A new type of galvanometer with electromagnetic damping and high frequency response.

4. An optical system which magnifies the galvanometer deflections and which gives a brilliant trace that can be observed in a brightly lighted room.

5. A simple method of taking photographs similar to an ordinary camera.

6. A large viewing screen for making tracings or for giving demonstrations to a group of persons.

7. Simplicity, compactness, and ruggedness comparable with the average electrical indicating instrument.

Specially prepared for ELECTRICAL ENGINEERING and based upon "A Portable Oscillograph With Unique Features" (No. 33-90) presented at the A.I.E.E. summer convention, Chicago, Ill., June 26–30, 1933.

Application

With this new oscillograph, wave forms which are recurrent can be both observed and photographed easily and accurately. Transient phenomena of short duration also can be observed and photographed. Since there is a spot of light on both film and viewing screen at all times, transient phenomena may be observed and photographed without a timing shutter. Although there is no device on the oscillograph for timing transient phenomena, the operator can tell when the transient occurs by watching the viewing screen. This procedure will be found satisfactory for many types of transients, especially those which are not of too short duration, and which do not have to be timed with great accuracy. It is expected that an instrument of this type will find many new applications for the oscillograph in general experimental and instructional work where size, ruggedness, and cost were limiting factors in previous designs.

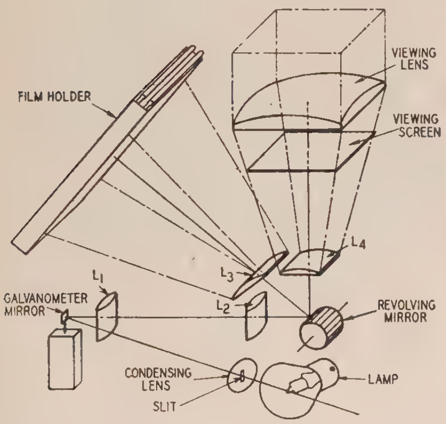

Fig. 1. Optical system of the new oscillograph which makes possible simultaneous viewing and photographing

The Optical System

The novel optical system, shown in Fig. 1, is one of the features which has made possible the design of this oscillograph. This optical system permits simultaneous viewing and photographing of wave forms and also gives an optical multiplication to the galvanometer deflections, thereby making it possible to obtain the equivalent of a long optical lever in a short space.

Referring to Fig. 1, the slit is illuminated by a standard 6-volt 32-cp automobile headlight lamp the filament of which is imaged on the galvanometer mirror by a small condensing lens. The lenses L_1 and L_2 are cylindrical with their axes at right angles to the axes of the cylindrical lenses L_3 and L_4. Optical multiplication is obtained by means of the lenses L_1 and L_2. The lens L_1 gives a reduced image of the slit directly in front of the lens L_2. This image, together with any motion imparted to it by the galvanometer mirror, is then enlarged by the lens L_2 on to the film. The size of the image on the film, in the vertical direction, is therefore fixed by the width of the slit and the overall magnification of the lenses L_1 and L_2. The other dimension of the image is determined by the height of the slit and the magnification of the lenses L_3 or L_4 which focus on the film and screen, respectively.

Directly above the viewing screen is a spherical lens, so placed that it gives an enlarged virtual image which is comparable in size to the image on the film. Without this lens, the image does not appear equally bright at all points on the screen. The lens corrects for this and also gives greatly increased brilliancy which is sufficient for viewing even in a brightly lighted room.

To secure a continuous time axis, the number of faces on the revolving mirror, and the angles subtended by the film and viewing screen, have been chosen so that there is always a spot of light entering on both the film and screen just as the previous spot is leaving.

An inside view of the oscillograph is given in Fig. 2, showing the arrangement of the different parts of the optical system. The small revolving mirror is driven by the friction between a wheel on the mirror shaft and a face plate mounted on the end of the motor shaft. The speed of the mirror, and hence the timing on the screen, is varied by sliding the motor back and forth to change the driving radius. This adjustment is made on the oscillograph panel by the operator.

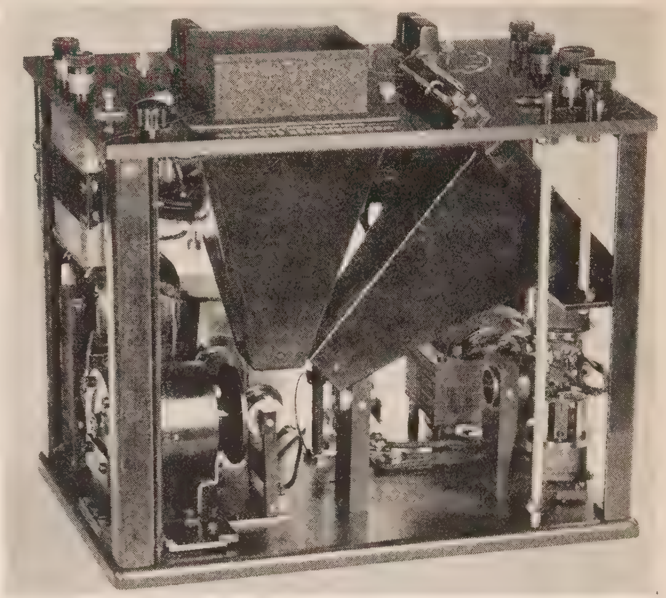

Fig. 2. Inside view of the new portable oscillograph

Rugged Galvanometer With Large Mirror

A galvanometer of very rugged construction has been designed especially for the oscillograph. This galvanometer, shown in Fig. 3, is of the moving iron type with a balanced armature form of construction. Although galvanometers of this type are not new to the art, this is the first time they have been successfully applied to the oscillograph. In place of the

vibrator ribbon as used in the moving coil galvanometer, this new galvanometer has a stiff torsional stem which supports the armature and furnishes the necessary restoring force to keep the armature centered in the air gap. In Fig. 4 is shown the armature and its support which is firmly clamped at one end in the galvanometer frame. The frequency range of the galvanometer may be extended simply by increasing the torsional stiffness of this support. In contrast to other types of galvanometers, the moving iron type becomes more rugged as the frequency range is increased.

The size of the galvanometer mirror in any oscillograph optical system is an important factor contributing to the brightness of the spot since the mirror will act as an aperture stop to decrease the illumination. With the galvanometer described, it is possible to make the mirror quite large and thereby obtain a very bright spot. The mirror shown in Fig. 4 is 1/8 x 5/32 in. and has approximately 15

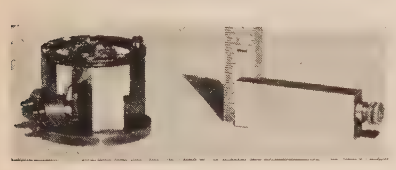

Fig. 3. Moving iron type of galvanometer used in the new oscillograph

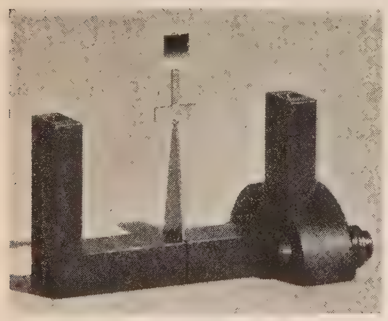

Fig. 4. Galvanometer armature and support

times the area of an ordinary oscillograph galvanometer mirror.

Damping Without Oil

In most galvanometers, it is necessary to use some form of mechanical damping, such as oil or rubber, but with the moving iron type it has been possible to get sufficient electromagnetic damping.

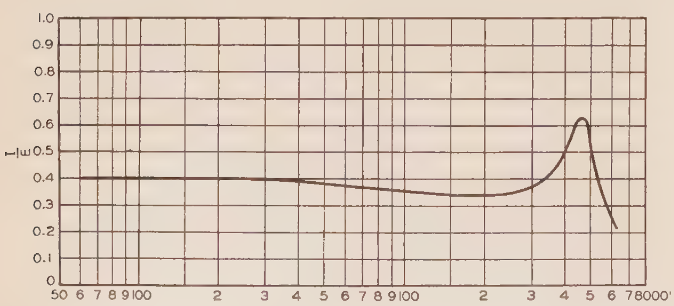

Fig. 5. Galvanometer frequency response

If a strong magnetic field is used, the motion of the armature at resonance will generate a back-voltage which will oppose the applied voltage to prevent any large deflections. The effectiveness of this back-

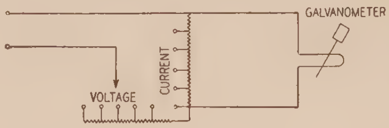

Fig. 6. Diagram of galvanometer circuit

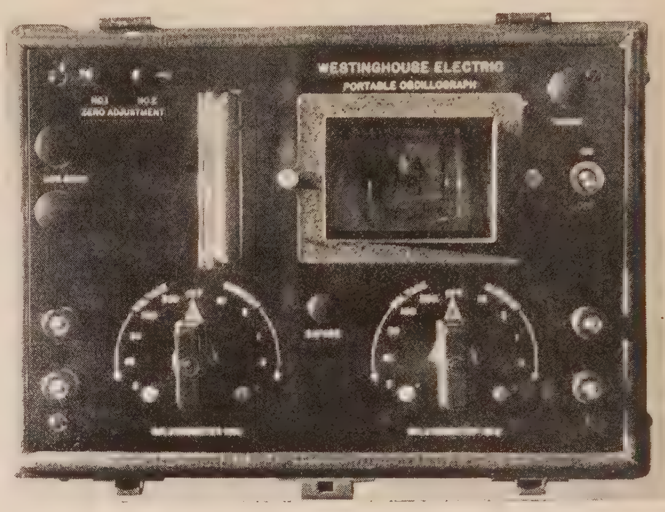

Fig. 7. Panel of the new portable oscillograph

voltage is determined by the total resistance of the circuit.

A typical response curve for the galvanometer used in the oscillograph is shown in Fig. 5. Although the damping obtainable with electromagnetic systems as used in the galvanometer is somewhat less than the desired value, it should be emphasized that it is practically independent of temperature, and the frequency response characteristic is therefore more satisfactory for a wide range of temperatures than that of an oil damped galvanometer.

In order to use a single galvanometer for making both current and voltage measurements, the circuit shown in Fig. 6 was devised for use in the oscillograph. This circuit makes the galvanometer response independent of the resistance of the external circuit and also provides a simple arrangement for making tap connections on the shunt and multiplier resistors. When making current measurements, a small resistance having a number of taps is permanently shunted across the galvanometer. The taps give the desired current range and the value of the shunt is such as to give the desired frequency response. It can be shown that this response is the same for any tap position. For making voltage measurements, another resistor is connected in series with the current circuit. This latter resistance has taps to cover the voltage steps, and is arranged so that on the lowest voltage tap, there is still sufficient resistance to give essentially a constant current to the shunted galvanometer circuit.

Compact and Light-Weight Design

The inside view of the oscillograph as shown in Fig. 2 gives an idea of the compact design. The over-all dimensions are 8 x $11^1/_2$ x 11 in. and the total weight is approximately 22 lb. The instrument is entirely self-contained and may be operated from a 110-volt 60-cycle lighting circuit without auxiliary attachments.

A top view of the panel, Fig. 7, shows how few controls are necessary to operate the oscillograph. Each galvanometer has a single switch for selecting the desired multiplier or shunt resistor. The values marked on the panel give the approximate d-c voltages and currents for a deflection of one inch. Both galvanometers may be used for measurements of potentials up to 250 volts or currents up to 10 amp without the use of external resistors. The control switches have a stop to prevent the operator from accidentally switching to the current side when connected to a voltage circuit. However, no damage will result to the instrument if this mistake is made, since both the resistors and galvanometers are protected by fuses.

Both film and viewing screen are in position for use at all times. When it is desired to take a photograph of any recurrent phenomenon, it is only necessary to press the "expose" button near the center of the panel. This button opens a shutter to the camera, and at the same time, places an overvoltage on the oscillograph lamp. Provision has been made to use either a standard cut film holder or pack with $2^1/_4$ x $3^1/_4$ in. film in a manner similar to that of an ordinary camera.

Although this oscillograph is a research development product, it will be made available in the near future in a form that will differ only in minor details from the instrument described.

Two Applications of Nonlinear Circuits

Design of a feeder voltage regulator having no moving parts, and a method of improving alternator stability are discussed in this article. Both schemes utilize nonlinear inductive circuits, and were developed by the authors while they were undergraduate students.

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THE principle of nonlinear inductive circuits, in which the current is not directly proportional to the applied voltage, has been known for a long time, but has been applied commercially only comparatively recently. It was suggested to the authors that further investigation of the phenomenon of nonlinear inductive impedance might be of value. Accordingly, it was decided to examine the possibilities of applying the characteristics of such circuits to the following practical problems:

1. The design of a feeder voltage regulator having no moving parts.
2. The improvement of synchronous machine stability.

No claim is made to the discovery of any radically new principle, and the authors regard their work on the subject merely as an attempt to contribute something to the knowledge of possible new applications of an already established principle. The experiments have disclosed the fact that the nonlinear inductive circuit can be applied to the above problems with some degree of success. The authors do not presume to estimate the commercial value of these 2 schemes, but believe that some further development of the ideas may be found practicable in the future.

I—A Voltage Regulator Having No Moving Parts

A feeder voltage regulator has been developed in a college laboratory that has a number of advantages over existing types of voltage regulators. In the most recent of several stages through which this development has passed, the voltage regulator makes use of the inductive nonlinear circuit of the 3-legged reactor, and is controlled by gas or mercury vapor hot cathode electronic tubes. The characteristics of this regulator as regards load voltage, regulator efficiency, and effect on line power factor, are comparable to those of other types of regulators. The regulator also has the advantages that there are no moving parts, relays are not required, hunting is

Essentially full text of a paper "The Application of Inductive Nonlinear Circuits to Some Electrical Engineering Problems," presented before an A.I.E.E. joint meeting of the Denver (Colo.) Section and the University of Colorado Branch, at Denver, Colo., April 29, 1932. This paper, written while the authors were seniors in electrical engineering at the University of Colorado, was awarded the Institute's 1932 national prize for Branch paper. *Not published in pamphlet form.*

eliminated, operation is noiseless, and the regulator probably would be cheaper to manufacture than existing types of induction regulators.

The regulator was developed from the fundamental characteristics of an iron-cored reactor which has a changing voltage-current relation as saturation is approached. With a reactor composed of a single coil wound on an iron core, as soon as the core begins to saturate the effective impedance of the reactor decreases with increasing current. The similar effect occurs with 2 coils mounted on a closed iron core. This case is analogous to that of a 2-winding transformer. The impedance of the primary decreases with increasing secondary current. This reduction takes place regardless of whether the secondary current is alternating current induced from the primary coil, or is direct current applied to the secondary coil.

This principle has been applied commercially in what is known as the "3-legged" reactor, shown diagrammatically in Fig. 1. With the outer coils wound so that their magnetomotive forces balance each other, a small amount of direct current in the central coil may control a much greater amount of a-c power in the outer coils. This arrangement has been used in modern theater lighting control equipment, in relays, and as an amplifier. As will be shown later in this article, the same principle is used in the new regulator.

Manually Controlled Regulator

One of the earlier arrangements of the voltage regulator, although not by any means the first, is that shown in Fig. 2. This circuit consisted of a booster-connected transformer supplying power to the motor through a step-down transformer and the reactive line. The saturable reactor was connected

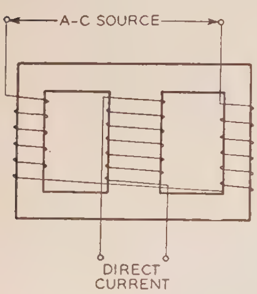


Fig. 1 (above). Schematic diagram of d-c controlled reactor

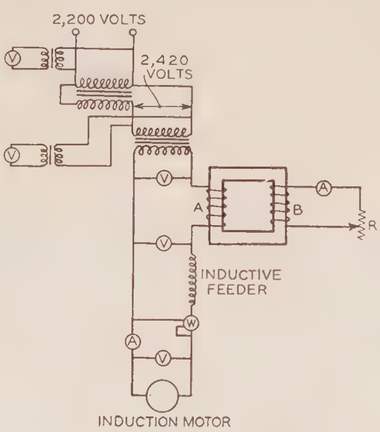
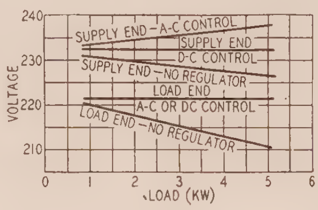


Fig. 2 (right). Booster transformer and saturable reactor regulating load voltage

in series with the secondary of the step-down transformer to reduce the boosted voltage to 220 volts at the motor terminals at no load. The voltage at the terminals of the 10-hp single-phase 220-volt induction motor was to be maintained constant by a change in the reactance of the reactor, as follows: As the motor was loaded, it drew a heavier and heavier current through the reactor and the reactive feeder, thereby producing considerable voltage drop between the supply end of the line and the load. This was compensated for, however, by reducing the impedance of the coil *A* through the medium of an increased current through the secondary coil *B*. As the load current increased, the resistance *R* was varied by hand, so as to permit more current to flow in *B*, which, as has just been pointed out, would reduce the voltage drop in *A* and offset the drop through the feeder. The voltage drop in the reactor requires the use of the booster transformer, which may be given a permanent setting.

This form of regulation was entirely successful, as is shown by the curves of Figs. 3 and 4, which give the results of regulation using both alternating and direct current in coil *B*. The circuit has the disadvantage, however, of requiring hand operation of the rheostat *R;* moreover, the over-all power factor



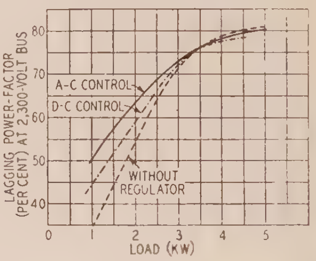


Fig. 3 (left). Manually operated reactor regulating voltage at the end of a reactive feeder

Fig. 4 (right). Over-all power factors obtained with and without reactor-regulator in circuit

of the system is slightly impaired at the higher loads. Oscillograms of the source voltage, the load voltage, and the load current were taken at no load, half load, and full load; these oscillograms show that practically no distortion of the wave form is caused by the use of such a regulator.

Automatic Regulator Developed

Attention was next given to the possibility of employing some form of vacuum tube control of the direct current in the secondary, or control, circuit of the reactor. Since a current of the order of 2 or 3 amp had to be handled, use of the ordinary type of vacuum tube was out of the question, and it was decided to experiment with a gas or mercury vapor filled hot cathode electronic tube. To this end, the circuit shown in Fig. 5 was established. Essentially, it consists of a booster-connected 2,200 to 220-volt, single-phase transformer taking power from a 2,300-volt line. The boosted voltage is then stepped down through another 2,200 to 220-volt transformer which supplies power through the regulating reactor and the reactive line to the load. The control coil *B* of the reactor is connected across the supply end of the feeder, in series with the rheostat *R* and the plate circuit of the tube, which in this case was a type *FG-67* thyratron tube. After considerable experi-

mentation with various values of grid bias on the tube and with various settings of the rheostat *R*, it was possible to effect entirely automatic regulation of the load voltage from no load to full load. The operation of the circuit was made to depend upon the

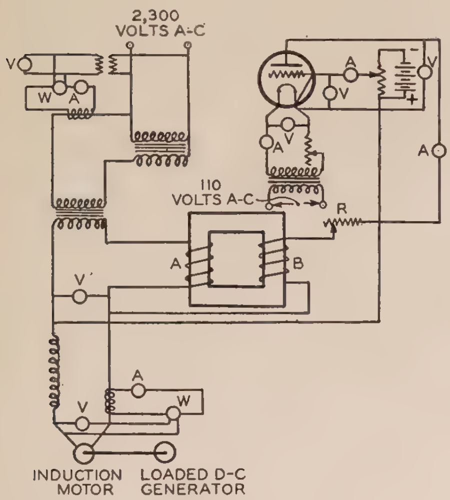


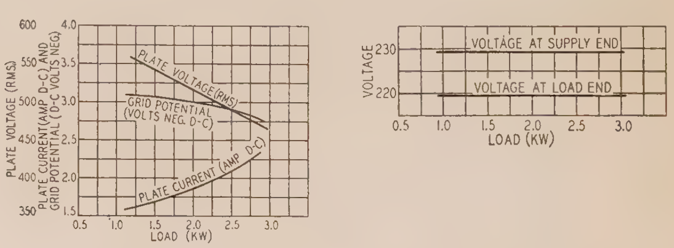
Fig. 5. Reactor controlled by electron tubes, automatically regulating load voltage

variation in the induced voltage of coil *B* occasioned by variation in the load current flowing through the primary coil *A*.

The voltage at the supply end of the feeder was connected in series with coil *B* in order to obtain sufficient operating voltage for the plate circuit of the tube. In this manner, a range in plate voltage of from 560 volts at no load to 460 volts at full load was obtained. It should be noted that the tube had an inverse voltage-current characteristic in this particular circuit, the plate current apparently increasing with decreasing plate voltage. Another point worthy of note is that, despite the application of a constant negative potential to the grid of the tube, the grid voltage actually became less negative as the plate current increased. This change in grid voltage is assumed to have been caused by a voltage drop within the tube from grid to filament, produced by the plate current. Since the tube exhibited some slight grid-potential plate-current control, this decrease in negative potential tended to increase the plate current and to assist the regulation. The results obtained with this system were plotted, and are shown in Figs. 6 and 7. They indicate that a satisfactory voltage regulator might be evolved in which the disadvantages of moving parts and contacts would be absent, and in which there would be no time-lag or hunting.

Three-Legged Reactor Applied

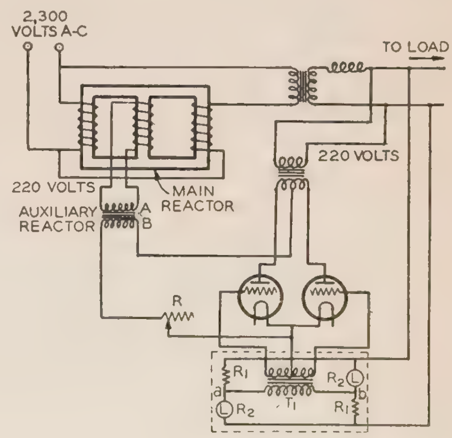
Attention was next given to an arrangement in which the booster and regulator would be combined in a single unit. For this purpose the 3-legged core of an old 13,200 to 220-volt, 3-phase transformer was used, and circuits were established as shown in the upper left hand corner of Fig. 8, except that in the early development the middle leg of the main reactor, instead of being connected to an auxiliary reactor and the tube circuits, was connected directly to a variable rheostat which shunted this middle coil. The booster consisted of the high voltage coil on one outer leg and the low voltage coil of the other outer leg. The low voltage coil of the central leg was used as the control coil, and the regulating current was adjusted by manual operation of the rheostat. The regulating effect produced here differs somewhat in its origin from that in the single-core reactor used



Figs. 6 (left) and 7 (right). Curves obtained with the reactor scheme shown in Fig. 5, automatically regulating voltage at the end of a reactive feeder

previously. In the other type of reactor, the reluctivity of the iron core was varied by varying the amount of current in the secondary coil. In the new system, however, the passage of additional current through the regulating coil on the center leg not only increases the flux density in the outer legs, but also decreases the amount of leakage flux from the outer legs passing through the center leg. The system appeared to have such good possibilities that it was decided to attempt to make it automatic. Before developing the electronic tube control, shown in Fig. 8, automatic control was secured by a water rheostat connected in the circuit of the center leg

Fig. 8. Three-legged reactor controlled by electronic tubes, regulating load voltage



of the reactor, and to which direct current was applied. With this arrangement, the setting of the water rheostat was controlled by a solenoid in the feeder circuit. The plunger of this solenoid rotated a lever arm which changed the setting of the water rheostat, thereby changing the amount of current flowing in the control circuit of the reactor. This regulator had a somewhat rising characteristic, but any desired characteristic could have been obtained

by changing the design of the solenoid and water rheostat.

More Satisfactory Equipment Evolved

It was next decided to apply electronic tube control to the 3-legged regulator, as shown in Fig. 8. In this combination the control current was not passed directly through the center coil of the reactor, but through coil B of an auxiliary reactor, the other coil of which was connected in series with the center coil of the main reactor. The control current for the auxiliary reactor was obtained by rectification from the load end of the line. For rectification, 2 electronic tubes were used, and their plate-filament circuits were connected to the line through a one-to-one ratio center-tapped transformer, in order to obtain full-wave rectification. The control of the tube plate current was effected by means of the circuit enclosed in the dotted rectangle at the lower right-hand corner of Fig. 8. The operation of the circuit is as follows: The tube plate current passes through the tube as an arc, the starting of which may be controlled by the grid. Once started, however, it cannot be further controlled by the potential on the grid, but may be stopped by reducing the anode voltage to zero, as is done periodically when an alternating potential is applied to the plate-filament circuit. Under such conditions, the tube operates with intermittent arc discharge, the average current of which is controlled by the grid voltage. The simplest method of operating a tube of this type is to impress alternating voltage on the anode and any desired voltage on the grid. The critical grid voltage which will start the discharge is a function of the instantaneous value of the anode voltage. As long as the grid voltage is more negative than this critical value, no current will flow in the plate circuit. Whenever the grid voltage becomes less negative than the critical value, plate current starts and continues for the remainder of the half cycle. Its value, once it starts, is limited only by the resistance of the circuit or load, and consists of pulses. The average current over any period will be equal to the area covered by the pulses divided by the time.

The circuit enclosed by the dotted rectangle in Fig. 8 is termed a voltage-sensitive bridge, and makes use of the phenomenon of nonlinear resistance. The bridge (see "Hot Cathode Thyratrons," by A. W. Hull, *Gen. Elec. Rev.*, v. 32, 1929, p. 213–23 and 390–9) was made up of dissimilar resistances, of which 2 opposite sides were slide-wire rheostats obeying Ohm's law, and the other 2 sides were tungsten filament lamps which deviate from that law, and whose equilibrium current varies as the square root of the applied voltage. Since the resistances follow different laws, evidently there can be only one value of terminal voltage which will allow the points a and b to have the same potential, and hence allow no current to flow through the primary transformer T_1. This voltage is defined as normal voltage. At this voltage the tubes are so nearly balanced that it is not certain whether they will operate or not; actually they operate about half the time. When they do operate, they feed more direct current through the coil B of the auxiliary reactor, thereby decreasing the impedance of the secondary coil A, which decrease in impedance permits more current to flow through the center coil of the 3-legged reactor. This increase in current in the center coil, as pointed out in previous discussions of this reactor, reduces the impedances of the outer coils and the voltage drop through them, thereby raising the load voltage. The transformer T_1 is so connected that any decrease in the load voltage will make the grids less negative during the half cycles when their respective anodes are positive, thereby allowing the plate current to flow and reduce the impedance of the 3-legged reactor, which in turn raises the load voltage, as just explained.

It is seen from the foregoing discussion that the attempt to produce a voltage regulator having no moving parts has been successful. The circuit operated satisfactorily at light loads, but the limited capacity of the tubes available prevented complete tests of the system under full load conditions. It was necessary therefore to return to manual operation of the control circuit in making tests of the efficiency and other important characteristics of the 3-legged regulator, but this in no way invalidates the possibilities of the system. Manual operation of the regulator was accomplished by connecting the coil B to a d-c generator, and varying the current by a rheostat in this circuit.

The curves of Fig 9 and 10 show the important characteristics of the 3-legged voltage regulator. It is seen that they are comparable to those of other types of regulators, and in addition the circuit has the following important advantages:

1. Absence of moving parts.
2. Relays are not required.
3. Hunting is eliminated.
4. Noiseless in operation.
5. Probably would be cheaper to manufacture than existing types of induction regulators.

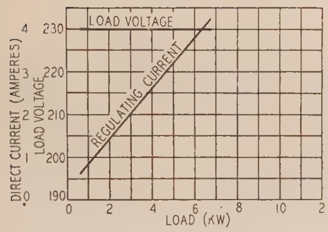
II—The Improvement of Synchronous Machine Stability

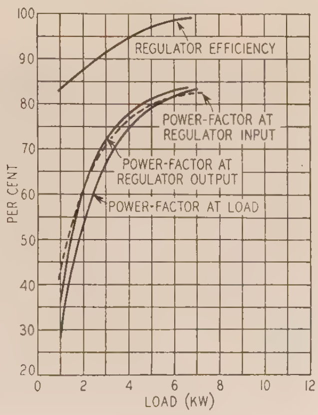
Much has been written in the past few years on the subject of power system stability, and many proposals have been made which aim to keep an alternator synchronized with its load when the power limit of the system has been approached.

It will be remembered that when a synchronous motor is being loaded from an infinite bus, the rotor of the machine drops back behind its true synchronous position by an angle depending upon the value of the load, the internal reactance of the machine, and the field excitation. Finally, when the load has reached a high enough value, the angular displacement is increased to its critical value, and the machine drops out of synchronism, even though the supply voltage is maintained constant. The critical load at which the machine drops out of step can be materially increased by increasing the field excitation.

Similarly, a synchronous generator can be caused to pull out of step with its load, if the power available to drive the generator is sufficient. The amount of load which a generator will carry successfully without falling out of step with the system is also dependent upon the internal reactance of the machine, and upon its field excitation.

Generator power limit or system stability problems do not necessarily arise during the normal operation of a system; however, an emergency may result from the automatic switching out of a generating unit, or from the tripping out of an entire power plant. Such an occurrence throws additional loads on the remaining generators of the system, so that any one of them may possibly be forced to operate at or very close to its maximum power limit. If the load imposed should happen to exceed the power limit of such a machine, it will fall out of step with the rest of the already heavily loaded machines, with the result that they also will drop their loads, and the whole system will break down.



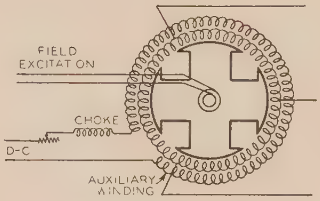


Figs. 9 (above) and 10 (right). Characteristics of 3-legged reactor as a voltage regulator

A Method of Increasing Stability

If there were some method by which the power limit of a synchronous alternator could be temporarily increased so as to carry it over the emergency, the stability of the power system could be materially improved. It is a recognized fact that to increase the power limit of a generator, the excitation must be increased, but at the same time the voltage must be kept constant. This has the effect of operating the machine higher up on the saturation curve. Several methods have been proposed to bring about the desired effect. It has been suggested, for instance, that the alternator terminals be shunted with large reactors. This has the effect of lowering the power factor on the generator, so that the field current must be increased in order to maintain normal voltage. In this way the machine is forced to operate higher on the saturation curve, and its power limit is materially increased. It is seen that this has the effect of apparently increasing the air-gap of the generator, or of stiffening the coupling. This proposal is sound, and tests in the laboratory confirm the theory. However, no one as yet has tried to build such a reactor for, say, a 50,000-kva alternator.

It might be thought that an ordinary vibrating type generator voltage regulator would take care of the matter of increased excitation; however, should the power factor of the system rise, the voltage of the alternator also would rise, owing to the magnetizing effect of the armature reaction. Thus the regulator would remain inoperative during such an emergency.



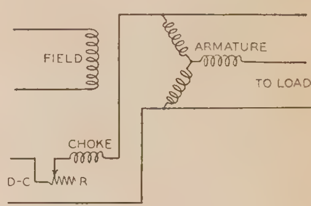


Fig. 11 (left). Alternator with an auxiliary d-c winding on the stator

Fig. 12 (right). Alternator stator connected to receive d-c component

Some engineers have advocated the use of high speed excitation systems which will, in any event, raise the field current of the alternator very rapidly. This is accomplished by causing a relay to shunt across the contacts of an ordinary vibrating type voltage regulator, thereby raising the field current very quickly, regardless of the voltage. This scheme and others that function somewhat in the same manner possess the disadvantage of causing the alternator voltage to rise along with the field excitation. When the system voltage rises, the load also rises, thereby increasing the load on the affected machine, and very little has been gained.

It may be emphasized, that in order to raise the load limit of a generator, the field excitation must be increased, but the terminal voltage must remain constant. This is, indeed, not a new principle; it has been repeatedly stressed in the writings of men who are recognized authorities on the subject of stability. The actual application of the principle, however, is not easy.

Application of the Nonlinear Circuit

The characteristics of the nonlinear inductive circuit make it readily adaptable to the solution of this problem. Referring to Fig. 11, let us suppose that an alternator is equipped with an auxiliary stator winding through which varying amounts of direct current may be passed. In series with this auxiliary winding is a heavy choke coil which will prevent the passage of any alternating currents which may be induced in it. Ordinarily, there is no current flowing in the auxiliary winding, but when an emergency arises and the load increases close to the critical value, a relay will act to force direct current through the auxiliary winding. The presence of this direct current will lower the reactance of the main stator winding by increasing the degree of saturation of the core, and at the same time the field current will have to be increased in order to maintain the flux necessary for constant terminal voltage. The net effect of

this operation is equivalent to an increase in the air-gap of the machine, so that a stiffer generator, with a correspondingly higher power limit, results.

It was not necessary to have a generator with an auxiliary winding in order to investigate the merits of the above theory. By connecting an alternator as shown in Fig. 12, a d-c component was passed through 2 phases of the Y-connected stator winding. This arrangement was tried out with satisfactory results, which will be further discussed later in this paper.

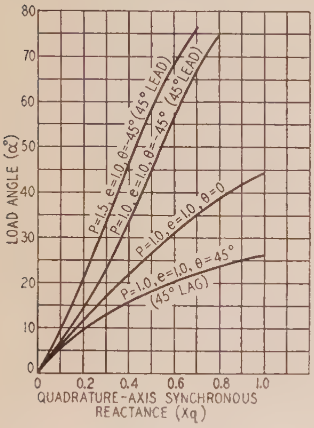


Fig. 13 (above). Theoretical curve for an alternator, obtained from the equation of tan α given in the article. Values of parameters are "per unit"

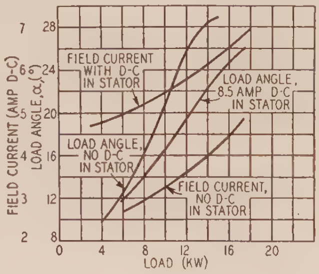


Fig. 14 (above). Curves showing the effect of a d-c stator component upon the load-angle vs. load characteristics of a 3-phase 15-kva 230-volt 60-cycle 6-pole alternator. Corresponding field current curves when operating at 192 volts, also are shown

Theory Supporting These Views

From the vector diagram of a loaded alternator having salient poles (see p. 939 of "Synchronous Machines," by R. E. Doherty and C. A. Nickle, A.I.E.E. Trans., v. 45, 1926, p. 912–42) the following equation may be derived

$$\tan \alpha = \frac{Px_q}{e^2 + Px_q \tan \theta}$$

where

α = electrical angle by which the terminal voltage of the machine lags behind the quadrature axis; it is termed the load-angle, or torque-angle, and is a measure of the displacement of the rotor from its true synchronous position, i. e., the displacement of the pole from the phase axis

P = total electric power, expressed as a fraction of the normal, or "rated" power of the machine

x_q = quadrature-axis synchronous reactance, expressed as a fraction of the normal reactance of the machine per phase; where normal phase reactance is defined as the ratio of rated phase voltage to rated phase current

e = terminal voltage, expressed as a fraction of the normal terminal voltage (i. e., "rated terminal voltage")

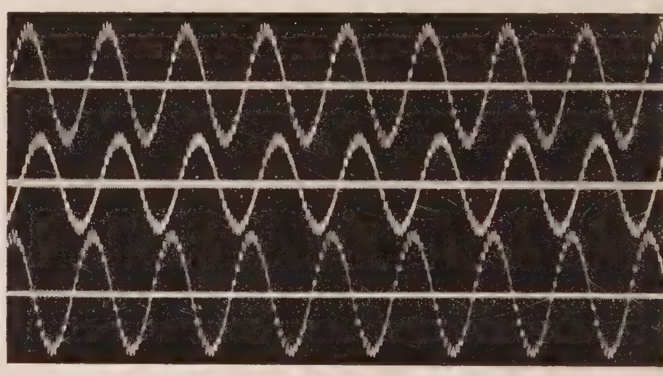
θ = power-factor angle, the angle by which the phase current is displaced from the phase voltage

In this equation, the quantities are defined in what is known as the "per unit" notation, rather than being expressed in percentages, or in absolute quantities, such as ohms. Such procedure makes for considerable simplification in computations based upon equations relating to these various machine constants. Hereinafter, unless otherwise stated, all quantities dealt with are per phase and per unit. As an example of the use of the per unit notation, consider some of the constants of the alternator used in these experiments, and which was rated 15 kva 230 volts, 37.6 amp per phase.

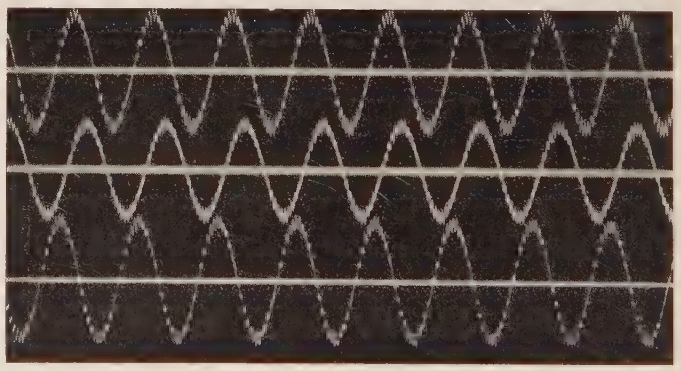
Normal phase voltage = 133 volts = 1.0 per unit
Normal phase current = 37.6 amp = 1.0 per unit

$$\text{Normal phase resistance} = \frac{133}{37.6} = 3.53 \text{ ohms} = 1.0 \text{ per unit}$$

The equation for tan α given above indicates clearly how the magnitude of the load angle depends upon the 3 factors: load, power factor, and quadrature-axis synchronous reactance, assuming the voltage to be maintained constant. Since the effect of x_q in the numerator of the above fraction is much greater than its effect in the denominator, anything that could be done to decrease x_q presumably would decrease the load angle α thereby increasing the stability of the machine and raising the power limit. This fact is demonstrated rather strikingly by the theoretical curves of Fig. 13, in which α is plotted against x_q for various values of θ and P, e being maintained constant at 1.0.



Alternator operating with no d-c component in stator winding



Alternator operating with 8 amp direct current in 2 phases of stator winding

Fig. 15. Oscillograms of terminal voltage of alternator, operating at 160 volts

Tests on an Actual Machine

Experimental verification of the above theory was next sought, and it was decided to measure the direct and quadrature synchronous reactances of the 15-kva 230-volt 6-pole alternator, by means of the slip method, both with and without direct current

flowing in the stator. Oscillograms were taken of line voltage and phase current with the machine rotating at slightly less than synchronous speed. The values of direct and quadrature synchronous reactances under the 2 conditions were as follows:

No Direct Current in Stator

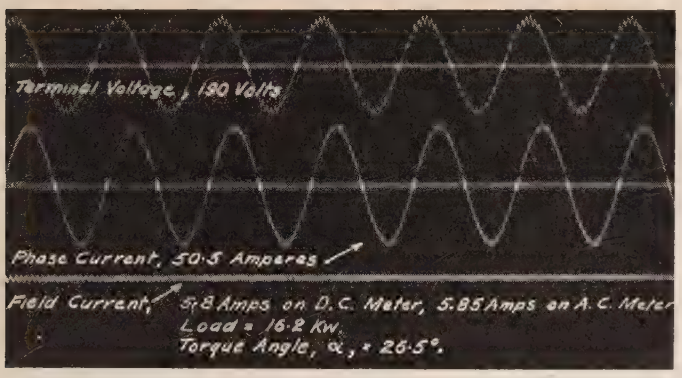
Direct-axis synchronous reactance, x_d = 2.88 ohms = 0.82 per unit
Quadrature-axis synchronous reactance, x_q = 1.90 ohms = 0.54 per unit

With 8.5 Amp Direct Current in 2 Phases of the Stator Winding

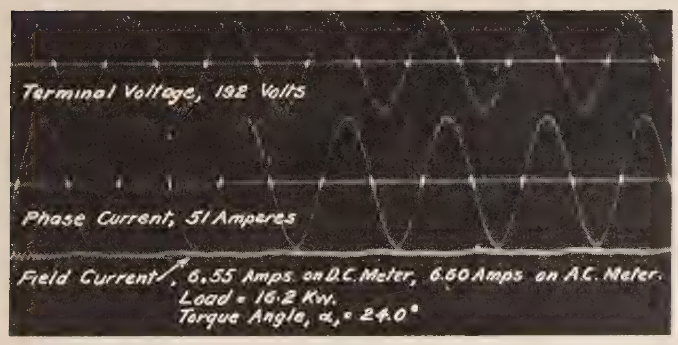
Direct-axis synchronous reactance, x_d = 2.32 ohms = 0.66 per unit
Quadrature-axis synchronous reactance, x_q = 1.67 ohms = 0.47 per unit

While the proportionate reduction in x_q was not as great as that in x_d, nevertheless, it was deemed sufficient to justify the next experiment, an investigation of the effect of the direct current upon the load-angle α with a view to substantiating the theoretical deductions.

The next test consisted of a load run of the same alternator at a terminal voltage of 192 volts (0.835 per unit), with observations of the load angle being made by means of a glow tube stroboscope shining



Alternator operating with no direct current in stator

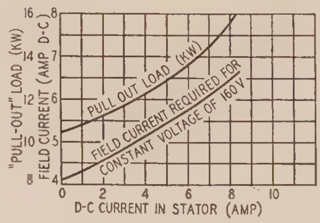


Alternator operating with 8.5 amp direct current in 2 phases of stator

Fig. 16. Oscillograms of terminal voltage, armature current, and field current when loaded

on a marked disk attached to the shaft of the machine and a circular scale mounted on the frame. The use of a terminal voltage of 192 was necessitated by the fact that the stroboscope used had to be operated from the terminals of the machine under test and at a voltage of 110 volts. To obtain these conditions, the voltage from line to neutral on the machine was adjusted to 110 volts and the stroboscope connected thereto. This resulted, of course, in a terminal voltage of 192 volts.

At first the machine was loaded in the ordinary manner, and observations were made of the following quantities for each load: load in kilowatts, terminal



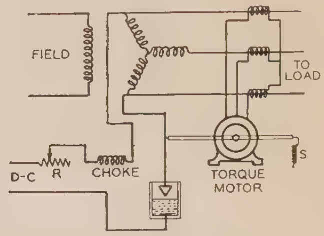


Fig. 17 (left). Effect of a d-c stator component upon the pull-out load of alternator operating at 160 volts

Fig. 18 (right). Automatic scheme for feeding direct current into the stator of an unstable alternator

voltage (constant at 192 volts), field current, and load angle. The procedure was then repeated with a direct current of 8.5 amp flowing through 2 phases of the stator winding. A comparison of the results of the 2 tests may be made upon reference to Fig. 14. It is seen that for the same given load, the torque angle was considerably less when direct current was present in the stator than when the machine was operating in the ordinary way. It should also be noted that there was a marked increase in the field current for the same terminal voltage, which, it will be remembered, was the desideratum for increased stability.

It might be thought that the direct current in the stator would distort the voltage wave, or cause such unbalance in the stator as to produce heavy induced currents in the field circuit. The oscillograms of the terminal voltage of all 3 phases, both with and without direct current, shown in Fig. 15 indicate but slight distortion in the voltage wave; while those of phase voltage, phase current, and field current in Fig. 16 (taken at a slight overload), show that only a slight a-c ripple is produced in the field circuit. This latter fact is all the more noteworthy because the machine used has no damper winding on the field structure.

As further proof of the efficacy of the method, the pull-out load of the machine was measured for various amounts of direct current in the stator, ranging from 0 to 8 amp. Here, again, it was impracticable to operate at normal voltage, because the d-c motor driving the alternator was incapable of carrying the loads involved without overheating. It was decided, therefore, to operate at 160 volts. The results of this test are shown in the curves of Fig. 17, in which pull-out load and field current required for constant voltage are plotted against stator direct current. It may be seen that with no direct current in the stator the load limit was 10.48 kw and that a field current of 4.1 amp was needed to maintain 160 volts at this load. When the d-c component in the stator was raised to 8 amp, however, the load limit rose to 15.6 kw, and the corre-

sponding field current to 6.5 amp; an increase in pull-out load of 48.6 per cent and an increase in field current of 58.5 per cent.

Automatic Control Applied

An arrangement was then set up by means of which it was hoped to apply the direct current to the stator automatically whenever the need for it might arise. In Fig. 18 is shown the loaded alternator with 3 Y-connected current transformers in the lines. The secondaries of these transformers were connected to the stator of a small 3-phase induction motor. The greater the load current, the greater would be the torque on the rotor of the induction motor. This torque acted in a counter-clockwise direction against the pull of the spring *S*. As the load increased, the induction motor would turn and dip the upper contact of the water rheostat into the water, thereby allowing direct current to flow into the stator of the alternator. The application of the direct current increased the degree of saturation of the stator core and tended to reduce the terminal voltage, but a vibrating type regulator (not shown) would act immediately to bring up the field current above normal for that voltage, so that the alternator would be in an over-excited state without any rise in voltage having taken place. The apparatus operated satisfactorily, and was, of course, so adjusted that no direct current was applied until the machine was dangerously near to its load limit. Only at such a time would the upper contact dip into the water rheostat to produce the desired effect. It may be noted that the system is effective regardless of the power factor, and regardless of any unbalance in the load.

Electrical Figures on Plates in Air

A recent investigation into the behavior of Lichtenberg figures and streamers extending out from an electrode resting on a glass plate coated on the opposite side with tin foil is reported in this paper. The new data offered throw considerable light on the formation and characteristics of these interesting figures.

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THE 2 SETS OF PHENOMENA known as Lichtenberg figures and Toepler's "Gleitfunken" or "spreading discharges" are closely related in that they originate in the same manner and the latter is only a further developed form of the former. Both phenomena have been studied extensively and various explanations of them have been offered, [1,2,3,4,5] but the new data offered in this paper throw considerable light on the formation and characteristics of these interesting figures. This work was undertaken at the instigation of Professor Matthias of the Berlin Institute of Technology, and because in a search of the literature relating to Lichtenberg and Toepler figures (some of which is reviewed in this paper) no very satisfactory explanation was found for the relation between the sizes of the positive and negative figures, the relation of the velocities of growth of the 2, and the increase in size of the figures as a function of time. Completion of the experimental work was made possible by a stipend from the "Verein Deutscher Ingenieure."

Summarized briefly, the more important findings of these experiments are as follows: Lichtenberg figures and streamers going out from an electrode resting on a glass plate coated on the other side with tin foil grow with an average radial speed of 20 to 315 km per second, or even more. The instantaneous speed of growth decreases with increasing size of the figure. The speed is dependent, for a given voltage surge, on the dielectric constant and thickness of the plate. Any variation of these that increases the capacitance per unit area of the plate causes an increase in the speed of growth and *vice versa*. A given variation of the dielectric constant or thickness of the plate produces a greater change in the speed of growth of negative figures than in that of positive figures. The per cent variation in speed of growth for figures of either polarity, resulting from a given variation of the plate constants, decreases with increasing magnitude of the applied voltage surge. The maximum current intake (for 2 figures in parallel) has been observed to be 45 amp at 60 kv (maximum value of voltage surge) and 120 amp at 85 kv. In one case the effective capacitance of 2 figures in parallel varied from an initial value of practically zero to about 8,000 cm in 3×10^{-7} sec, causing a reduction in the maximum value of the applied voltage wave of 25 per cent; the reduction in the rate of rise of the voltage for the same case was 30 per cent. The behavior of the figures supports the theory that the movement of electrons alone is principally responsible for their formation.

Full text of a paper recommended for publication by the A.I.E.E. committee on electrophysics. Manuscript submitted April 28, 1933; released for publication Sept. 28, 1933. *Not published in pamphlet form.*

1. For references, see bibliography at end of paper.

Review of the General Behavior of Lichtenberg and Toepler Figures

Brush Discharge and Streamer Discharge. Toepler has differentiated between 2 stages of the figures, which he calls "Gleitkorona" and "Gleitfunkenkorona," or "Polbueschel" and "Gleitbueschel," respectively. Equally descriptive English names are "brush discharge" and "streamer discharge." Lichtenberg figures belong to the first class. The true streamer discharges, which belong in the second class, appear under the influence of more powerful voltage surges.

The following characteristics of these figures can be investigated: (1) length attained, (2) speed of growth, and (3) current drawn. Using the familiar arrangement of a small electrode resting upon a glass plate coated widely underneath with metal forming the other electrode, these properties are found to vary with the voltage applied, the thickness of the glass, and the dielectric constant of the glass.

According to Toepler's results the size attained by the figures in the first stage depends only on the voltage wave, i. e., on the polarity, steepness of front, maximum value, and, to a degree, on the steepness of the tail. No difference was noticeable in this stage "for plates of the most widely varied thicknesses." The voltage of transition from the first to the second stage, however, is dependent on the thickness of the plate. This critical voltage is expressed as a constant times the square root of the thickness, the constant being somewhat different for the 2 polarities. As long as the discharge remains in the first stage, that of Lichtenberg figures, the radius of the positive figure is about twice that of the negative for a given voltage wave, and the figures are symmetrical.

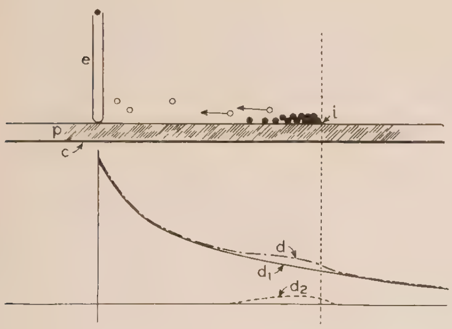


Fig. 1. Formation of surface charge and distortion of original voltage distribution with growth of electrical figure

As the voltage of the surge is increased, the discharges go over to the streamer state, in which glowing branched channels appear to be going out from the electrode. The appearance of these channels causes the figure to lose its symmetry, and gives it an unbalanced flower-like shape. Toepler's researches revealed that the maximum radial length attained by the figures in this stage depends not only on the form, size, and polarity of the voltage wave, but also on the capacitance per unit area between the 2 surfaces of the plate according to the following relation: Maximum radial length = a constant × (unit capacitance)². In this stage, as the figures become larger and larger, the difference in the size of the positive and negative figures approaches zero.

Mechanism of the Spreading Discharges

Capacitor Chain Theory. In order to explain this phenomenon of a discharge along the surface of the glass, Toepler first proposed the concept of a series of neighboring elementary capacitors formed by elementary areas of the upper surface and the coating of the lower surface. From this point of view the process of growth of a figure is as follows: A voltage wave reaching the electrode raises its potential high above that of the upper plate of the first elementary capacitor (i. e., of the neighboring surface) so that an arcover occurs between the electrode and the first capacitor. The latter is charged through the spark, and, as soon as its voltage is high enough, arcs over to the second capacitor. This second capacitor in turn is charged and arcs to the third, which then is charged, etc. By the use of a formula derived by Binder[6] on the basis of the differential concept just outlined, Jezek[6] was able to confirm by calculation his measurements on the velocity and current intake of streamer discharges along glass tubes filled with mercury.

Expanding Ring Surface Charge Theory. A truer idea of the process also was suggested by Toepler in the paper referred to, in which the production and movement of ions and electrons, and their influence on the original voltage distribution along the glass, are taken into consideration. Staack[5] also supports his theoretical discussion on this conception, which, however, must be modified in the light of the results of recent work done by Erwin Marx[7] and C. E. Magnusson.[4] These modifications will be dealt with later.

Referring to Fig. 1, a sudden application of voltage to the electrode *e* causes ionization of the air immediately surrounding its tip. Particles of opposite polarity are attracted to the electrode. Par-

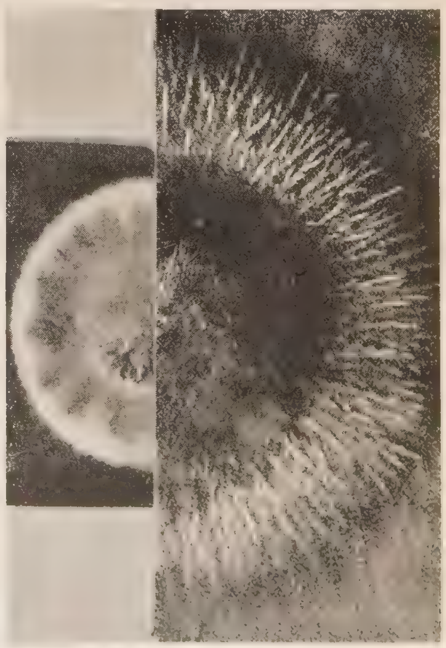


Fig. 2. Right half of positive figure and left half of negative figure made under identical settings of "firing" gap and "cut-off" gap (actual size)

ticles of the same polarity experience a force away from the electrode and against the surface of the glass, so that they form a ring-shaped surface charge. The potential distribution d_2 along the plate due to this surface charge combines with the original distribution d_1 to form a new potential distribution d. This raises the gradient along the plate at the point i enough to cause ionization, the surface charge expands, and the process continues until the gradient at the outer rim of the surface charge becomes less than that necessary to ionize air.

Results of Previous Experiments

Jezek[6] determined simultaneously by spark gap methods the maximum rate of voltage rise and the maximum current intake. Using the current measurements in a formula in which the velocity of growth appears as a function of current intake, voltage, and capacitance per unit length between the 2 surfaces of the tubes used, he determined the probable values of velocity. He found the velocity to be directly proportional to the voltage. His tubes had values of capacitance per unit length ranging between 4 and 9 cm, and for one of them a voltage of 64 kv maximum value caused a maximum speed of growth of 5,000 km per second. The observed maximum current was not directly proportional to the maximum voltage, as it increased from 57 to 125 amp for maximum voltages of 26.4 and 45 kv, respectively.

According to the measurements of Mueller-Hillebrand[8] the velocity of growth of Lichtenberg figures produced by voltages between 2.5 and 18 kv can reach a value as high as 500 km per second.

P. O. Pedersen[2] has determined an expression for the radius of the figure as a function of time in the form: $r = R(1 - e^{-\alpha t})$ in which r = radius at any instant and R = radius finally attained. From

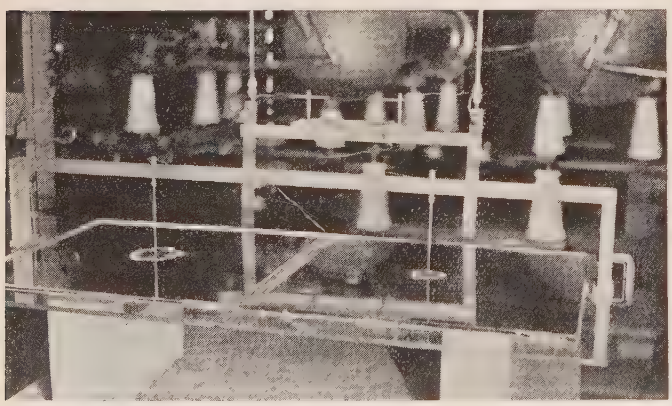


Fig. 3. Test plate mounting; surge generator in background

this the velocity is $v = \alpha R e^{-\alpha t} = \alpha(R - r) = v_0 - \alpha r$. For atmospheric pressure, v_0, the initial velocity, was found to be 700 km per second for positive, and 300 for negative figures. The empirical constant α was given as about 2.5×10^9 for positive and 1.9×10^9 for negative figures (for r in cm).

In his 1921 article Toepler quoted measured or estimated values of speed of growth in air that varied from 3,560 to 55 km per second.

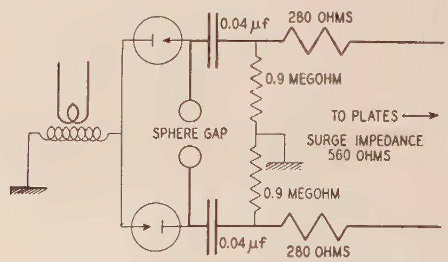
While the present paper relates only to the rate of growth of these figures in air it may be of interest to note here that Staack[5] found for one value of voltage velocities of growth on plates in transformer oil of 18 km per second for positive figures and 9 for negative figures which were constant throughout the entire development of the figure.

Discussion of Previous Results

Range of Velocities Observed; Polarity Difference. The preceding material presents 2 features of interest: (1) observed velocities of growth covering a very broad range, the smallest differing by more than one order of magnitude from the largest; and (2) the difference in the speeds of growth of positive and negative figures, and the practical disappearance of the difference when the figures become very large. The fact that the results of Toepler, Pedersen, and Staack (in his work under oil) show continually in the first stage velocities of growth for positive figures approximately 2 times the velocities for negative figures is very disturbing. If such a simple ratio really exists it should be exactly determinable experimentally and justifiable theoretically. If not, it should be recognized as an accident.

Explanation of Wide Velocity Range. The wide difference in the values of speed of growth observed

Fig. 4. Diagram of connections of surge generator



by different experimenters probably may be traced to variations in the several experimental conditions such as, for instance, the thickness of the plate, the dielectric constant of the plate, the form of the voltage wave used, etc. As shown by Toepler, the length attained by streamer discharges is a function of the capacitance per unit area of the plate. The original object of the work described here was to investigate the dependence of the speed of growth of the figures on the thickness and dielectric constant of the glass. The results include data showing an increase of (average) speed of growth in the ratio of 1.84 to 1 for positive figures and 2.98 to 1 for negative figures when the thickness of the plate was decreased in the ratio of 1.63 to 1 with no change in the dielectric constant of the plate. (The fact that this effect is greater for negative figures than for positive ones is of significance in the theory of formation of the figures, and will be discussed later.) Decreasing the thickness of the plate in the ratio of 1.98 to 1 caused an increase in the velocity of growth of as much as 2.51 to 1 for positive figures and 3.97 to 1 for nega-

tive figures. These figures show in a convincing way that observed velocities very easily might differ by one order of magnitude or more, when, as in the case of Jezek's tubes and the plates used in these experiments, the ratios of thickness vary between 6 to 1 and 11 to 1.

Experimental Procedure of Present Work

Glass plates were used for the tests described in this paper. As quickly as possible after the application of a voltage surge to the plate it was sprinkled with a mixture of red oxide of lead and sulphur. As these 2 powders together are dusted on the plate, the lead oxide takes on a positive charge and the sulphur a negative one. Thus if a plate that had just been exposed to a negative surge was sprinkled with the mixture, the red oxide of lead was attracted to the negative ring surface-charge left on the glass, thus marking the limits the figure had reached.

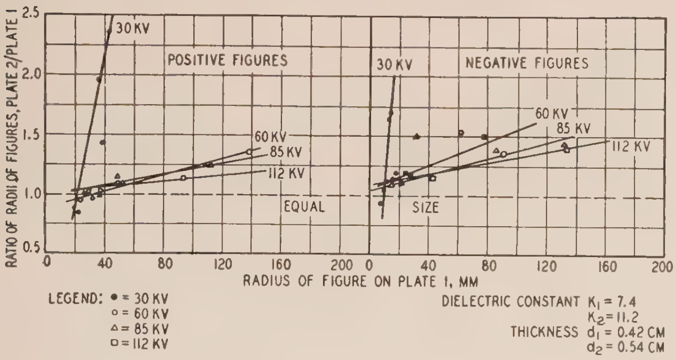


Fig. 5. Comparison of plates 1 and 2: variation of figure size with dielectric constant, thickness approximately the same

Similarly the limits of the positive figure were marked with the yellow sulphur. To prepare the plate for recording another figure it is only necessary to sweep off the powder and remove any remaining surface-charge by rubbing with the hand, finishing the rubbing with a clean dry cloth to leave the surface perfect. Photographs of typical figures recorded in this way are reproduced in Fig. 2. In one respect, this method of recording is preferable to the photographic plate method: It shows the final position of the charges on the plate, whereas the photographic plate gives a trace of their entire motion.

In making the tests, 4 glass plates were used; 2 of them had a dielectric constant of about 7, the other 2 of about 11. One plate of each of these pairs was about 5 mm thick, the other about 1 cm. The plates always were tested 2 at a time, in different combinations of 2 plates in parallel for each test. This was done to eliminate undesired variables from the test conditions. With the plates in parallel it was certain that exactly the same voltage wave was impressed on both plates, and any difference in the resulting figures was bound to be due alone to differences in the physical properties of the plates. A needle gap was connected in parallel with the plates, its spacing being used to regulate the duration of the voltage on the plates. As is well known, if a voltage little more than just sufficient to cause arcover of a needle gap (on d-c test) is impressed upon the gap very suddenly, an interval of time will elapse before the discharge actually occurs; this is because ionization does not occur over the entire gap at the same

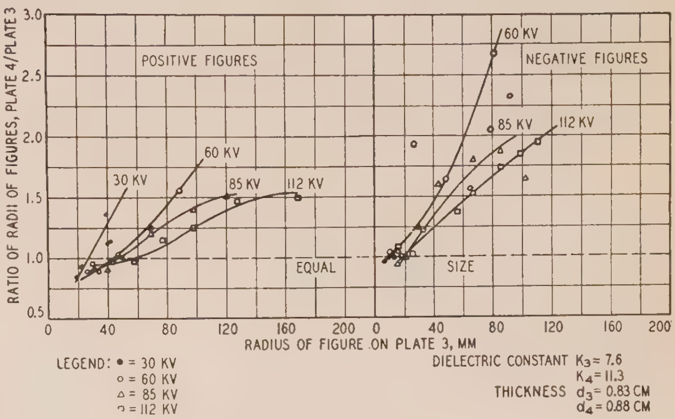


Fig. 6. Comparison of plates 3 and 4: variation of figure size with dielectric constant, thickness approximately the same

time, but begins near the points and spreads toward the middle. If the maximum value of the surge voltage applied to a needle gap is appreciably above the d-c arcover voltage, the time lag is very short, and, as it proved, of the right duration to allow the electrical figures to attain a convenient size.

Figure 3 shows clearly the arrangement of plates, electrodes, and needle gap; in addition 2 negative figures may be seen. The figures are in the second stage, no longer round and symmetrical, but with somewhat scalloped rims due to the formation of streamers. Figure 4 shows the diagram of connections for the surge generator used in the tests. The connection to the plates was made over an indoor transmission line with a surge impedance of 560 ohms. To eliminate oscillations from reflected waves a noninductive resistance of 280 ohms was included in each side of the line at the surge generator.

Test Routine. The thin plate with the low dielectric constant was called No. 1, the thin plate with the high dielectric constant No. 2, and the thick plates with the low and high dielectric constants Nos. 3 and 4, respectively. Tests were made on parallel combinations of Nos. 1 and 2, 3 and 4, 1 and 3, and 2 and 4. Surges having maximum values of 30, 60, 85, and 112 kv were used. For any series of tests at one voltage the needle gap was set at 0.5, 1.0, 1.5, 2.0 cm, etc. After each surge the electrical figures formed were measured and their sizes recorded. As soon as the figures had entered the second stage and had become unsymmetrical, the *greatest* radius was recorded in each case.

Somet mes the measurements for duplicate tests were quite consistent, but more often they were not. Obviously consistent data were possible only when

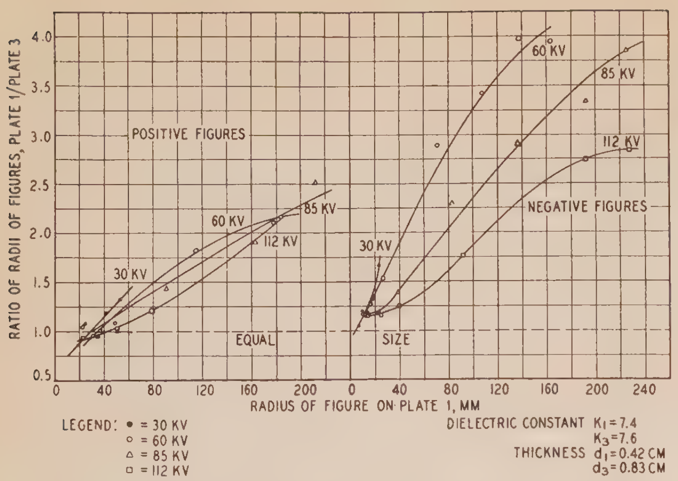


Fig. 7. Comparison of plates 1 and 3: variation of figure size with plate thickness, dielectric constant approximately the same

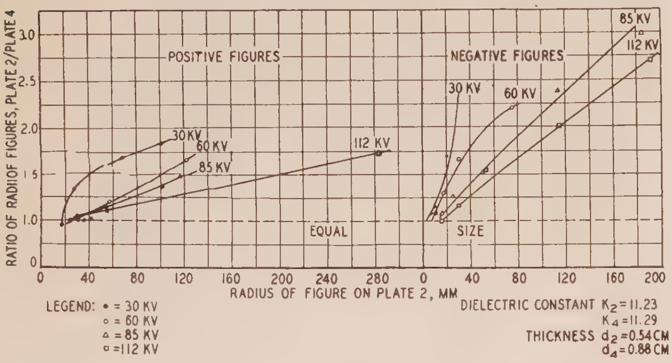


Fig. 8. Comparison of plates 2 and 4: variation of figure size with plate thickness, dielectric constant approximately the same

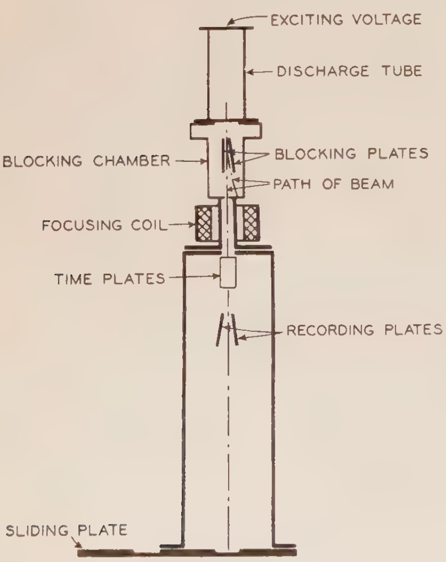


Fig. 9. Cathode ray oscillograph of the type developed at the Berlin Institute of Technology, which was used in these tests

under fixed conditions identical figures could be obtained in several tests. For this, the nature of development of the figures must be such as to produce identical figures under identical conditions, and the time lag of the "cut-off" needle gap must remain accurately the same for the same voltage and spacing.

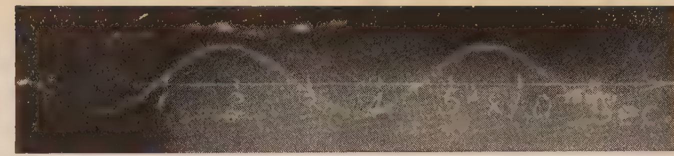


Fig. 10. Oscillogram of voltage on test plates

Sine wave is for timing; its wave length is 111 m, period 3.7×10^{-7} sec

It is probable that neither of these conditions was satisfied.

Each measurement was repeated 3 or more times, until a good average was available or until, through the trend of the readings, a probable value became evident. The rule of always measuring the greatest radius of the figure was not entirely satisfactory, because successive figures formed under the same voltage and needle gap settings were often of very different shapes. Perhaps a more reliable guide would have been the area of the figure.

Results Obtained

Data obtained are presented in graphical form in Figs. 5 to 8, inclusive. Figure 5 shows the ratio of the radii attained in the same length of time on plates 1 and 2 plotted as ordinate against the radius of the figure on plate 1. Figure 6 shows similar data for plates 3 and 4, while Figs. 7 and 8 are for plate combinations 1 and 3, and 2 and 4, respectively. An attempt was made to fit the curves as well as possible to the available points. In some cases, such as the 60-kv curve of Fig. 6 for negative figures, the scattering of the points was so severe as to render a justifiable choice of curve practically impossible. In other curves, such as the positive curves of the same set, and the negative curves of Fig. 7, the data seem reasonably unequivocal.

Remembering that each point gives the ratio of the radii of 2 figures formed in the same length of time, it is clear that it also represents the ratio of the average velocities of growth (up to that point of time) of the 2 figures. The effect grows with the size of the figures in every case, since the curves have a positive slope. The velocity of growth was greater for the plate with the greater dielectric constant or the smaller thickness, i. e., with the greater capacitance per unit area between surfaces. This finding agrees with the work of Toepler and others. Detailed study makes apparent 1 or 2 other features of interest.

For a given size of figure, the ratio of the greater average velocity to the smaller average velocity decreases with increasing surge voltage, as shown by the decreasing steepness with increasing voltage for all curves. Therefore, the effect of varying the dielectric constant or plate thickness decreases in importance with increasing voltage, for a given size of figure.

A second point of interest is the polarity difference apparent in the curves. Each negative curve is steeper than the corresponding positive one, so that higher values of the velocity ratio are observed for negative figures than for positive ones. The nega-

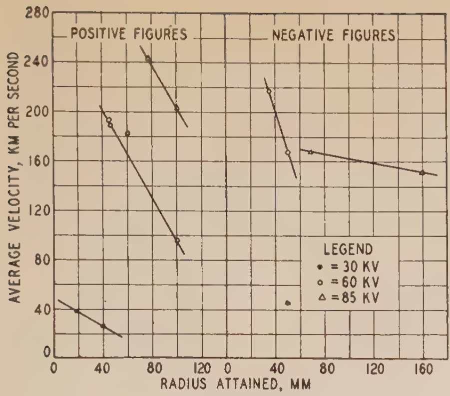
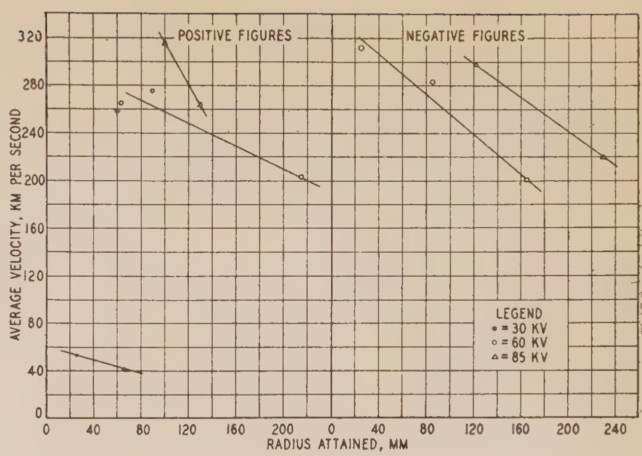


Fig. 11 (left). Growth velocities of electrical figures on plate 1 versus radius attained, for different voltages

Fig. 12 (right). Growth velocities of electrical figures on plate 2 versus radius attained, for different voltages



tive figures are therefore more sensitive to variations in the plate constants.

Experiments With Cathode Ray Oscillograph

For this part of the work, a cathode ray oscillograph was used to make records of the voltage applied to the test plates (see Fig. 9). The time of duration of the voltage surges on the plates, and the actual average speed of growth of the figures thus could be determined. Here again 2 plates were tested simultaneously. Most of the tests were made with the 60-kv maximum surge. A few were made at 30 kv, and a few at 85 kv; at the latter voltage the induced disturbances due to the necessary proximity of the oscillograph and the surge generator were so great as to preclude any attempt to work at 112 kv. One of the surge voltage records is shown in Fig. 10. Although not entirely free from disturbances, the length of time from voltage rise to voltage cut off can be determined accurately.

Most of the tests were made on plates 1 and 2 in parallel, and the data presented apply to them. On Fig. 11, the average velocity of growth of figures on plate 1 is plotted as ordinate against the radius of the figure. There are not enough points to determine significant curves, but straight lines are drawn through points taken at the same voltage to indicate that the average velocity decreases with increasing size of the figure. Similar data for plate 2 is plotted in Fig. 12. The velocities recorded are seen to be greater for higher voltages, as is to be expected, and lie in the range of from 20 to 315 km per second.

Effect of Polarity Difference

The data given cannot be used for a strict comparison of the relative velocities of positive and negative figures, as the voltage values given are the voltages for which the firing gap of the surge generator was set, i. e., the maximum voltage that would have appeared on the *open* transmission line. The presence of the test plates on the line, and of the rapidly increasing effective capacitance of the figures growing on them, caused some reduction in the steepness of the wave front and in the maximum value attained by the voltage wave. This reduction was greater for positive figures, because of their (already known) greater initial speed of growth, than for the negative ones.

To verify this, a 3-curve oscillogram was made with a 60-kv wave applied to the line. The first curve was for the open line, the second was with the test plates connected to record negative figures, and the third with the plates connected for positive figures. Measurements of the curves showed that whereas with open line the 60-kv wave had a maximum rate of rise of approximately 850 × 10^6 kv per second, with

Fig. 13. Oscillogram showing reduction of traveling wave of voltage caused by formation of electrical figure

Upper trace shows voltage (60 kv) on open line; lower trace, voltage appearing on plates 1 and 2 during formation of positive figures. Sine wave is for timing

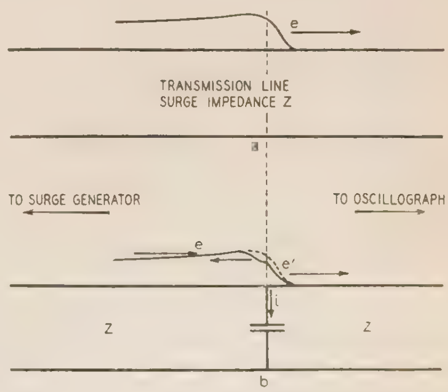


Fig. 14. Effect of lumped capacitance on traveling wave

the negative figures the steepness was reduced to 520 × 10^6 kv per second and the maximum value attained to 44.2 kv; with the positive figures the 2 values were 236 × 10^6 kv per second and 31.6 kv. A similar oscillogram for the 85-kv wave showed a maximum value for positive figures of only 47.6

kv. For a given setting of the firing gap, therefore, the negative figures were formed with a higher actual voltage on the electrode than the positive figures. Notwithstanding this favorable condition for greater negative velocities, the positive velocities recorded were greater than the negative ones for the same firing gap voltage and the same radius of figure.

Current Intake and Effective Capacitance of the Figures

The reduction of the magnitude of the traveling wave of voltage from its open line value caused by the current drawn by the figures may be used to calculate this current. Such calculations were made for the 2 voltage curves shown on the oscillogram in Fig. 13. The conditions in the 2 cases are made clear schematically in Fig. 14. For the open line, a voltage wave of instantaneous value e travels along the line from the surge generator to the oscillograph, as in Fig. 14a. If the test plates are across the line the voltage enters their point of connection with the same instantaneous value, e, emerging from this point with the reduced value e' due to the current i entering the plates. For such a connection the instantaneous value of the current taken by the plates can be calculated by the formula $i = 2(e - e')/Z$, in which Z is the surge impedance of the line.

The voltage waves from Fig. 13 are reproduced in the drawing of Fig. 15 with voltage and time calibration, together with the current taken by the plates, calculated by the preceding formula. The curve in Fig. 16 shows the instantaneous value of the effective capacitance of the figures, calculated from the i and e' curves of Fig. 15, as a function of time.

Discussion of the Theory of Formation of Streamer Discharges

Figures Formed by Movement of Electrons Alone. By means of experiments in which Lichtenberg figures were formed under the influence of a perpendicular magnetic field, Magnusson[4] has proved that both positive and negative figures are formed by the movement of negative charges. Since electrons would move much faster than any complex ions that might be present, the outer boundary of the figure, and thus its size, must be determined by the motion of the electrons. The velocity of growth observed for the electrical figures of from 2×10^6 to 3×10^7 cm per second could not be attained by positive ions for the field strengths involved, at atmospheric pressure. (Rogowski gives the velocity of charges moving in a field of 30 kv per centimeter at room temperature and atmospheric pressure as between 10^7 and 10^8 cm per second for electrons, and 10^5 cm per second for positive ions; *Arch. f. Elek.*, v. 16, 1926, p. 502.) Therefore, the explanation of the manner of growth of these figures as given in the fore part of this paper under heading "Mechanism of the Spreading Discharges" must be revised to the extent that the leading part in the movement of charge for the figures of both polarities be assigned to the negative charges, the positive ions being regarded as fixed.

The Polarity Difference. In the formation of the positive figures the ring-shaped surface charge is formed by the withdrawal of the electrons from the freshly ionized district, the positive ions remaining practically fixed in their positions on the plate. The expansion of the ring is effected similarly: As electrons are attracted to the electrode, the ring-shaped area in which a positive charge predominates widens. For the positive figure, at a stage of considerable development, the probable conditions are those shown in Fig. 17. The negative figure, however, grows by the movement of the electrons out along the plate, the ring formed by the negative surface charge truly expanding in this case. Fig. 18 illustrates this.

The radical difference in the formation of the positive and negative figures, therefore, is this: In the former the electrons move freely back and slightly up from the rim of the figure, impelled by the high gradient there; in the latter the electrons must move out along the plate against which they are driven, their movement impeded by repeated collisions with the plate.

Any exact analysis of the relation between the electron velocity and the speed of growth of the positive figure is difficult to make. It is the author's hypothesis, however, that the positive figure grows with a speed approximately equal to that of the electrons in the high gradient at the rim of the figure. Regarding the problem as a differential one, suppose that ionization has just taken place in the elementary area of radial extent δr. The theory that the prerequisite for ionization in the next greater elementary ring be the removal of the newly formed electrons over the distance δr is a tenable one. Under this hypothesis the difference in speed of growth of the positive and negative figures becomes the difference in speed of electrons moving (1) freely in a high field, and (2) in a field of about the same value that has a

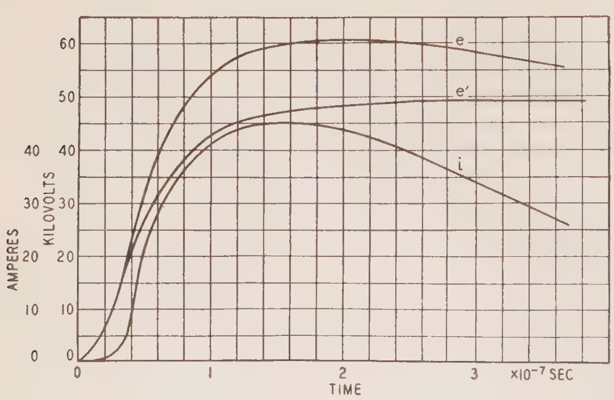
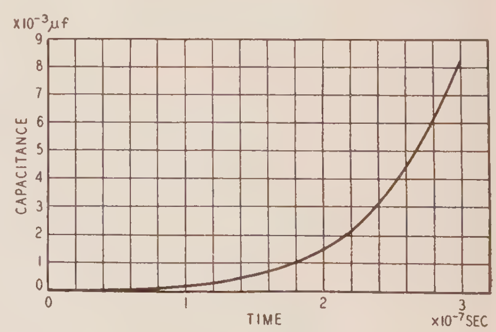


Fig. 15 (left). Voltage-time and current-time characteristics of electrical figures

e, e′, and i. See Fig. 14

Fig. 16 (right). Capacitance-time characteristic of electrical figures



component impelling them against the plate. That this retarding force is of such a value as to have produced in the experiments of some authors a ratio of size and velocity of the 2 sorts of figures of 2 to 1, must be regarded as a coincidence. The hindering effect due to impact against the plate can be said to vary with the magnitude of the vertical component of the field. The fact that for large figures the velocity of growth (average) and the size of the negative figure approach those of the positive can be traced to the decrease of the vertical component of the field with increasing distance from the electrode.

Effect of Varying Unit Capacitance of Plate. The speed of growth of the figures thus depends directly on the field strength at the rim. The original volt-

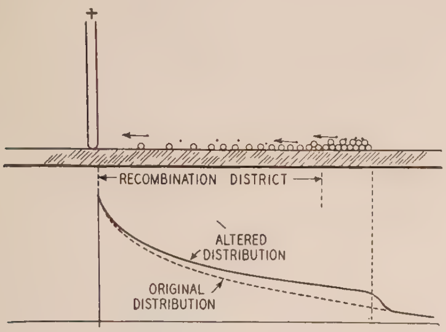


Fig. 17. Probable conditions during formation of positive figure showing effect on voltage distribution

age distribution along the plate influences the manner and rate of growth of the surface charge, and thus, indirectly as well as directly, influences also the field strength at the rim. Variations in the dielectric constant or thickness of the plate are significant because of their effect on the original voltage distribution and on the superposed potential of the growing surface charge.

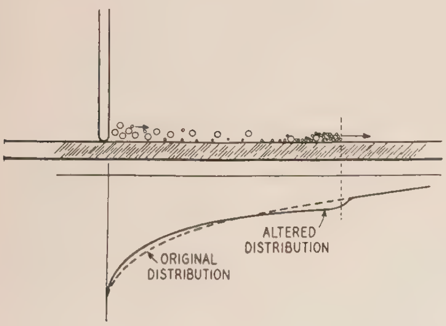


Fig. 18. Probable conditions during formation of negative figure showing effect on voltage distribution

Increasing the dielectric constant and reducing the thickness of the plate both result in the bunching of the lines of force toward the center, around the electrode. The gradient and its component along the plate is increased in the region directly around the electrode, with the result that they are diminished farther out. The curves of original voltage distribution along the plate for a (hypothetical) plate of dielectric constant 1, and for one of a higher dielectric constant, are shown in Fig. 19. A reduction of the thickness of the plate may be thought of as producing the same result.

The greater velocities and sizes of figures on plates with higher values of capacitance per unit area between the surfaces is to be attributed to the more intense ionization in the region around the electrode directly at the start. A surface charge of higher density which is able to propagate itself along the plate with greater rapidity is set up at once. The

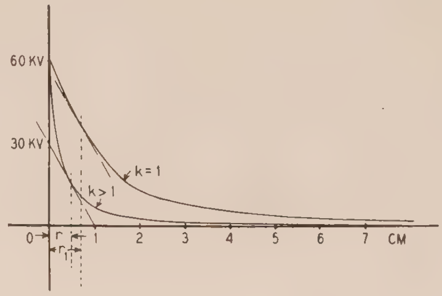


Fig. 19. Effect of an increase in dielectric constant of plate on voltage distribution

growth of the figure is expedited further, with the plate having greater unit capacitance, by the bunching of the lines going out from the surface charge in its progress across the plate, and the resulting increase of the gradient at its rim.

At some distance out from the electrode, the lines of force leaving it enter the plate almost vertically. This vertical gradient causes the retarding of the movement of the electrons by impact against the plate in the case of the negative figure. The reduction in this gradient caused by the bunching of the lines at the center upon an increase in the unit capacitance of the plate permits the negative surface charge to move across the plate with fewer collisions with the plate. This explains the greater response of the negative figures to an increase in the unit capacitance.

Effect of an Increase in the Applied Voltage. The decrease in the ratio of growth speeds on plates with different dielectric constants or different thicknesses with increasing voltage applied is explainable through the decrease in significance of the space charge—everything considered for a given radius of figure attained. The growth of the space charge on the plate, and its furtherance of the formation of the figure, is a cumulative process. A given difference in velocity and amount of space charge at any stage of the simultaneous development of figures on 2 plates in parallel is magnified with farther growth. An extension of the region in which ionization can take place without help from the space charge, by producing a higher initial gradient along the plate, cancels some of this magnification and reduces the difference in the figures.

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Effect of Oil Pressure on Insulation Strength

The effect of high oil pressure upon the electrical strength of cable insulation has been subjected to a series of tests which are reported in this paper. These tests show that an increase in pressure will result in an increase in the breakdown voltage, the magnitude depending upon the time duration of the test. Although in the long time tests breakdown voltage was doubled by pressure increased from 1 to 6 atmospheres, no improvement was secured with impulse tests by a pressure increase up to 11 atmospheres.

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IMPROVEMENT in cables, which combine liquid and solid dielectrics, has come largely through the study and control of gaseous electrical phenomena. This is because through circumstances of use in the field, gases enter the cable structure and the resulting electrical discharges in these gas layers cause deterioration ultimately leading to failure.

The steps in improvement have led successively first to the abandonment of the heavy solids or petrolatums as treating materials and then to the oil filled cable, where the possibility of entrapped and dissolved gases is reduced to the minimum possible.

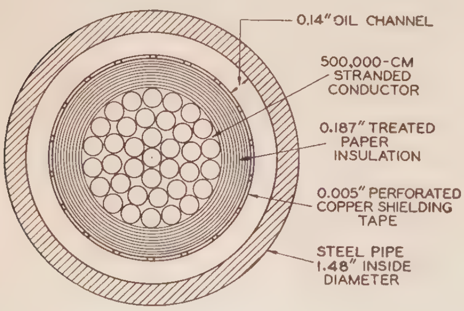

Fig. 1. Cross sectional view of 500,000-cir-mil single-conductor cable tested in steel pipe

Granting, however, that some residual gas remains, its effect should be reduced if it is subjected to high pressure, for it is a well-known fact that the breakdown voltage of a gas increases with the pressure almost linearly. Furthermore Koch[1] has shown that the dielectric strength of liquids shows a similar effect but that of solids does not. In order to study the combined dielectric (oil and paper) tests have, therefore, been run to investigate the effect of high oil pressures on (1) the long time or endurance dielectric strength; (2) the short time dielectric strength; and (3) the impulse voltage strength of treated paper insulation. The first 2 of these tests have been previously reported.[5]

Table I—First Long Time Voltage Test

Kilovolts	Average Stress, Volts Per Mil	Hours
75.0	400	300
85.0	450	307
93.5	500	383
103.0	550	326
112.0	600	163
121.5	650	160
131.0	700	6

Table II—Second Long Time Voltage Test

Kilovolts	Average Stress, Volts Per Mil	Hours (Held)
37.5	200	25.0
46.7	250	53.0
56.1	300	24.0
65.5	350	42.0
74.8	400	168.0
84.1	450	168.0
93.5	500	165.0
103.0	550	165.0
112.0	600	165.0
122.0	650	225.0
131.0	700	192.0
140.0	750	1.4

Long Time Voltage Tests on Cables

Two long time or endurance voltage tests were run on actual cables. The first test was made on a 10-ft length of 2/0 single-conductor cable insulated with 0.187 in. of oil treated paper. The treating oil was a heavy cable oil of viscosity 580 sec Saybolt at 60 deg C. Porcelain terminals were provided and oil pressure supplied by a small motor-driven pump automatically controlled to hold 80 lb per sq in. pressure above atmospheric. With the small diameter of the cable and a lead sheath thickness of 0.125 in., the lead sheath withstood this pressure without appreciable stretching during the test. A long time step-up voltage test was applied holding each step for 2 weeks, as shown in Table I. The life at the last step was 6 hr.

Tested at atmospheric pressure, the life of similar cable is of the order of 20 to 200 hr at 350 volts per mil. There is therefore approximately a doubling of the long time breakdown voltage when the oil pressure is increased from atmospheric pressure to a pressure of 80 lb per sq in. above atmospheric.

Since any application of high pressure to cables in service necessarily would prevent the use of a simple lead sheath, the second test was run on a 45-ft length

Full text of "The Effect of High Oil Pressure Upon the Electrical Strength of Cable Insulation" (No. 33-65) presented at the A.I.E.E. summer convention, Chicago, Ill., June 26–30, 1933.

1. For all numbered references see list at end of paper.

Table III—Short Time Voltage Test

Pressure, Lb–Sq In. Gauge	Dielectric Strength (Volts Per Mil) Rapidly Applied Voltage	Minute Step-Up
0	1,280	970
25	1,600	1,400
55	1,790	
60	1,670	
65		1,650
112	2,010	1,870
172	2,190	1,990

Table IV—Impulse Breakdown Voltage With 1-10 μsec Impulse Wave

Pressure, Lb/Sq In. Gauge	Kilovolts, Electrode No. 1	2	3	4	5	6	7	8	9	Average	Volts Per Mil
0	52.5	55.0	50.0	47.5	55.0	50.0	52.5	50.0	47.5	51.0	3,400
30	50.0	52.5	47.5	52.5	52.5	50.0	50.0	47.5	47.5	50.0	3,340
60	47.5	50.0	52.5	52.5	52.5	52.5	52.5	47.5	52.5	51.0	3,400
90	52.5	55.0	50.0	45.0	47.5	52.5	50.0	55.0	50.0	50.8	3,380
120	47.5	47.5	50.0	50.0	50.0	50.0	52.5	52.5	50.0	50.0	3,340
180	57.5	52.5	52.5	52.5	52.5	55.0	57.5	52.5	57.5	54.2	3,620

of cable, without lead sheath but provided with a 5-mil copper spiral shielding tape. This cable was drawn, untreated, into a length of steel pipe and provided with porcelain terminals. The physical dimensions are shown in Fig. 1.

The cable was vacuum treated after installation and filled with the oil normally used on oil filled cable. The oil had a viscosity of 100 sec Saybolt at 100 deg F. Voltage was applied and held according to the schedule in Table II. Failure occurred at 750 volts per mil. Again the result was a dielectric strength double that to be obtained at atmospheric pressure.

Short Time Tests on Treated Paper Sheets

The short time dielectric strength tests were made on sheets of treated cable paper, and were carried out over a range of pressures. A small pressure tank was constructed in which sheets of paper (total thickness 0.015 in.) after previous treatment in oil, could be placed and tested under pressure up to 200 lb per sq in. Tests were made between 2-in. diam disk electrodes, with edges rounded to a $^1/_8$-in. radius (A.S.T.M. electrodes). Two series of runs have been made so far; first, a rapidly applied test in which the voltage was raised uniformly at 0.5 kv per sec until failure, and second, a minute step-up test starting at 40 per cent of the rapidly applied breakdown and increasing the voltage in 1 kv steps each held for 1 min until failure. The results, expressed in volts per mil for these tests are given in Table III. (The values given are the averages of 10 individual tests.)

Impulse Tests on Treated Paper Sheets

The impulse voltage tests were made on the same type and thickness of treated paper samples, using the same electrode and equipment, as were the short time tests described above. A 1–10 testing wave was used, i. e., one which obtained its crest value in 1 μsec and diminished to ½ crest value in 10 μsec. The tests were conducted by starting with an impulse wave of 37.5-kv crest and increasing this value 2.5 kv between successive applications until a breakdown was indicated by a surge crest ammeter.[2,3,4] The results of these tests are shown in Table IV.

Conclusions

These tests indicate that at power frequencies and under long time application of voltage there is a considerable increase in endurance strength of oil treated insulation at pressures of several atmospheres. Under impulse stresses, however, practically no benefit is derived from increased pressure. The effect of pressure on dielectric strength is greater the longer the time of voltage application, being negligible for the impulse voltage tests of only a few microseconds duration and a maximum for the long time endurance test. This is shown in Fig. 2.

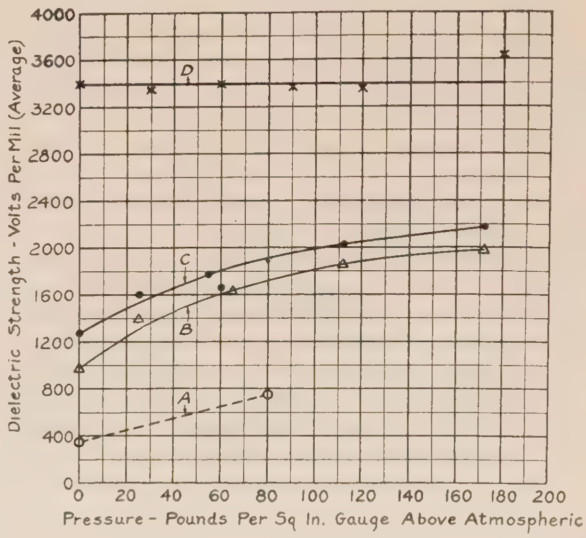

Fig. 2. Summary of test results

A. Long time test on cable
B. Minute step-up voltage test on oil treated paper sheets
C. Rapidly applied voltage test on oil treated paper sheets
D. Impulse voltage test on oil treated paper sheets

Credit is given to G. M. J. Mackay for suggesting this work and to J. B. Felter, J. A. Weh, B. H. Thompson and H. P. Kuehni, members of the General Engineering Laboratory staff for obtaining the data herein reported.

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Theory of Primary Networks—Part I

A study of voltage regulation and load distribution is given in this section of the author's work on power system primary networks, solutions of practical operating problems under both normal and abnormal conditions being given. Simple equations are presented to enable the distribution engineer to determine the proper settings of compensators and contact-making voltmeters; and other practical problems are discussed and answered.

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PRIMARY networks used in power system distribution are considered in this paper from the point of view of operating engineers responsible for such networks, all practical conditions of steady state operation being considered. Previous literature on primary networks has been devoted largely to comparative economics. It is not intended to rediscuss these factors here, but rather to consider the actual design and operation of the network itself. Part I of the paper is devoted to load distribution and voltage regulation, and Part II (to appear later) will be concerned with short-circuit and relay studies.

The material presented in the present section consists of:

1. A discussion of emergency load distribution, with charts showing the distribution of load in a network under various emergency conditions, and with analyses showing the influence on emergency load distribution of such factors as automatic regulation, power factor, impedance of the 4-kv ties, etc.

2. A discussion and analysis of normal network operation and design as influenced by such factors as voltage regulation, circulating currents, and unbalanced load.

As an aid to the analytical work in this paper, an exact mathematical analysis of the regulated network was developed, and is given in general form in the Appendix. Although this method of analysis is applied here to primary networks, it is perfectly general and should be useful in analyzing any network having a multiplicity of regulated feed points.

The particular questions which it has seemed advisable to study in the present section of the paper are as follows:

1. When a transmission line feeding a primary network is taken out of service, how does the load carried by this line distribute among the network units remaining in service?

2. Quantitatively, what advantage in load distribution is gained by staggering the network loads on a given transmission feeder over concentrating adjacent loads on a given feeder?

3. What effect does the automatic regulating equipment (tap-changers or induction regulators) on the network transformers have on the distribution of load under normal and abnormal conditions?

4. Can the compensator used in conjunction with the regulating equipment be adjusted to limit circulating currents (due to differences in tap positions on the network transformers as well as to differences in the angles of the impressed primary voltages) to a desirable minimum, to aid in uniformly distributing a normally unbalanced load, and at the same time to give adequate over-compounding during peak load?

5. What maximum angular difference between supply voltages on the various primary feeders is permissible?

6. What procedure should be used in adjusting the compensator to give optimum performance?

These various factors have been studied analytically and by actual tests on networks in operation. In addition a number of calculating-board studies have been made. The conclusions arrived at here as a result of these studies, and the quantitative data obtained are thought to be quite reliable and should prove useful in the design and operation of primary networks.

Load Distribution Under Emergency Conditions

An important factor which affects the design of a primary network is the load distribution under conditions of both normal and emergency operation. It is desirable that the network be designed so as to permit all of the network transformers to share the load as uniformly as possible. No trouble usually is experienced in obtaining good load distribution under normal operating conditions providing adequate 4-kv ties are incorporated in the design. In some rare cases where the load density is extremely light, it may be desirable to use high reactance transformers to insure uniform load division.

More important than the problem of normal load distribution in network design is that of emergency load distribution. In order that a primary network may be designed to have adequate reserve capacity under the emergency condition of a transmission line which feeds the network being out of service, it is necessary to know how the load carried by that feeder divides among the network units remaining in service.

A variety of networks differing in size and construction have been studied with this problem in mind, and in the light of these studies the fundamental principles of emergency load distribution have been established. Primary networks may be very small, as for example those shown in Figs. 1*A* and 1*B*, or they may be quite large similar to that shown in Fig. 2. It is necessary to consider both the large and the small network to determine the limiting factors in load distribution.

Initially, networks are usually very small, only 3 or 4 units being tied together. The 2 networks shown in Figs. 1*A* and 1*B* are typical initial layouts and are very similar to 2 networks which are in

Full text of "Theory of Primary Networks, Part I—A Study of Voltage Regulation and Load Distribution on Primary Networks" (No. 33-85) presented at the A.I.E.E. summer convention, Chicago, Ill., June 26–30, 1933.

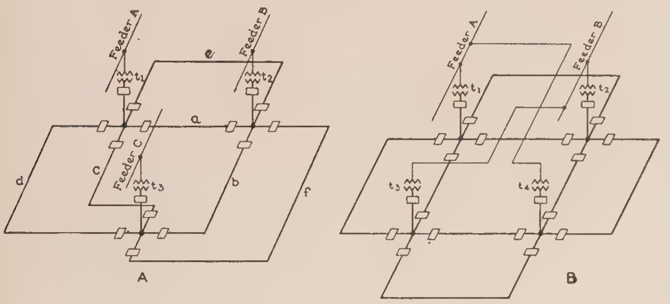
operation at the present time. The network shown in Fig. 1*A* is a symmetrical layout of 3 units, each being supplied by a separate transmission feeder. If feeder *C* is taken out of service the load carried by unit 3 distributes uniformly between units 1 and 2 owing to the symmetry. Even though all of the 4-kv ties are not of equal impedance, the load division still will be fairly uniform if the units are all thoroughly tied together.

To illustrate this fact, load data on an actual network in operation are given in Table I. This table shows that in spite of the normal unbalance in load and the poorly linked network, fairly good emergency load distribution is obtained.

Table I—Load Data on an Actual Network

Feeder Out	Load on t_1.	Load on t_2.	Load on t_3.
	73	63	80
A	0	95	121
B	90	0	126
C	103	113	0

Above loads are in per cent of normal. The above data were taken on a network similar to Fig. 1*A* but with ties *e* and *f* open. The transformer reactances were 5.5 per cent, and the 4-kv ties had impedances as follows: $a = (4.54 + j2.56)$, $b = (3.64 + j2.06)$, $c = (4.15 + j1.87)$, and $d = (12.30 + j10.70)$.



A. 3-unit network B. 4-unit network

Fig. 1. Typical small sized primary networks. These are characteristic of initial layouts

Now consider the network shown in Fig. 1*B*. This network of 4 units is fed by 2 lines, units 1 and 4 being supplied by feeder *A*, and units 2 and 3 being supplied by feeder *B*. If feeder *B* is out of service the load carried by units 2 and 3 will distribute uniformly between units 1 and 4 owing to the symmetrical layout. If each of the 4 points were fed by a separate line the emergency capacity of the network would be greater by the capacity of one unit than that of the layout as shown. Under this condition, if one of the units, say unit 4, were out of service, units 2 and 3 would each take approximately 35 per cent of its load and unit 1 would take the remaining 30 per cent. (These values are based upon the assumption that the 4 internal ties are 4-per cent overhead lines, the 4 external ties are 7-per cent overhead lines, and the transformers have 6-per cent reactance.)

Experience has shown that networks of a size up to about 8 units may always be laid out in such a manner that the load carried by any feeder will distribute uniformly between the units remaining in service when that feeder is out of service. In larger networks the units adjacent to the transformers out of service will absorb more of the load than the more remote units. In order to determine the emergency load distribution in an extensive network, the layout shown in Fig. 2 was studied. An extensive calculating board study has been made on this particular layout, the results of part of which are shown in chart form in Figs. 3, 4, 5, and 6. By exercising some care, these results may be applied directly in designing any large sized network (assuming of course that the network is not too loosely tied together).

The curves of Fig. 3 show how a normal 100 per cent load carried by transformer 23 would distribute among the remaining units if transformer 23 were taken out of service. Thus, assuming the impedance of the network main to be 4 per cent (1,500-kva 4-kv base), it may be noted from the curves of Fig. 3 that the 4 units immediately surrounding unit 23, i. e., units 16, 22, 24, and 30, each take 7.3 per cent of the load originally carried by unit 23 (only the curve for unit 16 is plotted in Fig. 3 since the other 3 are identical to it owing to symmetry). Other units more remote from unit 23 take correspondingly smaller percentages of the total load.

A set of curves similar to those of Fig. 3 are shown in Fig. 4 for transformer 39 out of service. It may be noted that the distribution in this case does not differ greatly from that obtaining in the above case with unit 23 out. For example, from Fig. 4, units 32 and 38 each take 7.8 per cent of the load carried by unit

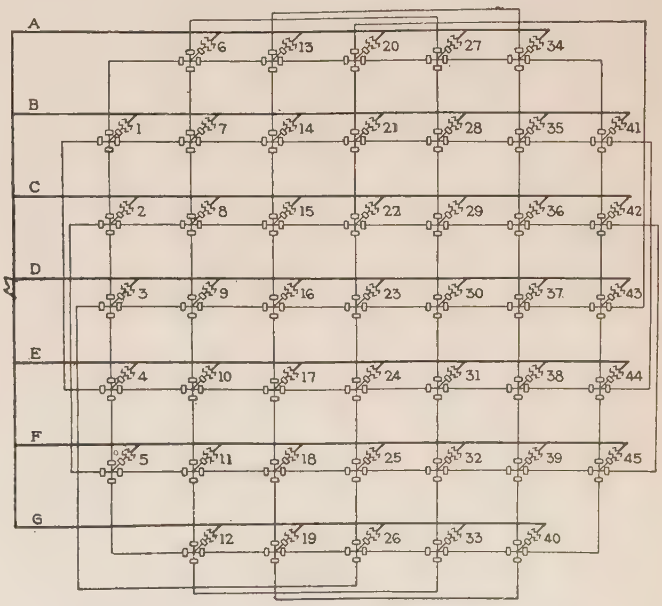


Fig. 2. Typical large sized primary network

This network was studied in regard to the various aspects of emergency load division

39 as compared with the 7.3 per cent of the load carried by unit 23 taken by units 16, 22, 24, and 30 in the above case. Space does not permit the printing of charts for other key transformer positions. However, the 2 sets of curves shown in Figs. 3 and 4 represent the 2 extreme current distributions for any one transformer out of service, all other outages giving distributions intermediate to these. Therefore, it should be fairly easy to estimate emergency

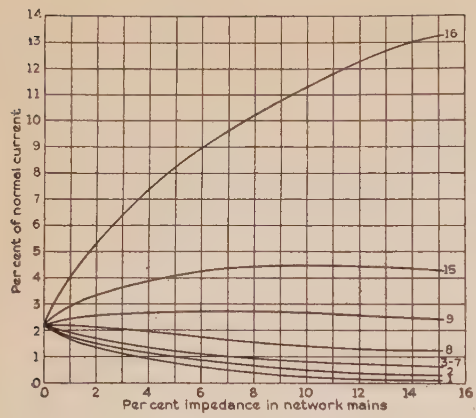
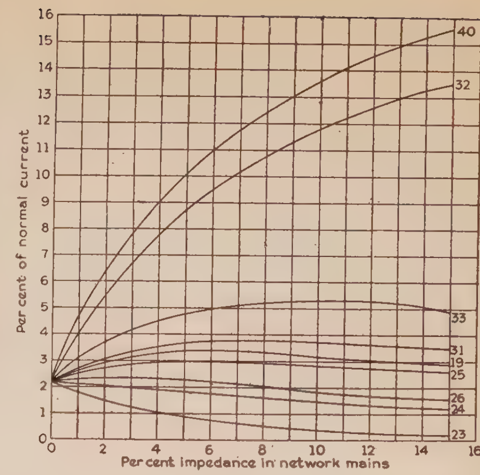


Fig. 3. Showing how the load normally carried by unit 23 in Fig. 2 distributes among the units remaining in service when 23 is out

Transformer reactance 6 per cent. Percentage values on 1,500-kva 4.3-kv base

Fig. 4. Showing how the load normally carried by unit 39 in Fig. 2 distributes among the units remaining in service when 39 is out

Transformer reactance 6 per cent. Percentage values on 1,500-kva 4.3-kv base



load distributions for any large network with reasonable accuracy from the data in charts of Figs. 3 and 4.

In a network of the size shown in Fig. 2, each transmission line would feed from 2 to 5 network units, the number depending upon certain economic factors. In order to obtain the most uniform division of load under emergency conditions, it is desirable that the network units supplied by any one feeder be non-adjacent to each other, i. e., staggered. For example, suppose units 11, 23, and 39 to be supplied by a common feeder. If this feeder were taken out of service unit 24 would receive the most severe overload. In this case, again assuming 4 per cent network mains, unit 24 will receive 7.3 per cent of the load carried by unit 23 (from Fig. 3) and it will receive 1.8 per cent each of the loads carried by units 11 and 39. If each unit were normally loaded to 90 per cent of full load kilovoltamperes, the emergency load on unit 24 will be approximately 0.9 (100 + 7.4 + 1.8 + 1.8) or 99.9 per cent of full-load kilovoltamperes. (The error involved in superposing the several load components arithmetically to obtain the total is small and may be neglected.)

A further examination of the data in Figs. 3 and 4 will demonstrate that the loss of a transmission feeder in a network of fairly large size need never impose an excessive overload on any transformer.

Transmission Feeder Arrangement

As pointed out above, the conventional method of feeding a network is to stagger the network units connected to any one feeder. For example, units 6, 22, 38, and 26 in Fig. 2 might be fed by one feeder, units 7, 23, 39, and 19 by another, etc. An alternative method would be to feed a group of adjacent network units from a single transmission line. The network in Fig. 2 is shown with this type of transmission layout. It is recognized that this sort of layout imposes a greater emergency overload burden on certain parts of the network when a transmission feeder goes out of service. However, it has been suggested that this latter method is more economical since the additional cost of interlacing the transmission lines more than balances the cost for the somewhat increased reserve transformer capacity required for the second arrangement.

In order to determine the probable maximum emergency overloads in networks whose feeders supply a series of adjacent units, the network of Fig. 2 was studied with the feeder arrangement as shown. The curves of Fig. 5 show the distribution of the load carried by feeder *A* when feeder *A* is out of service. Similarly the curves of Fig. 6 show the distribution for feeder *D* out of service. (Note that all loads are given in percentages of the normal load for any one transformer.) It may be noted that the maximum overload on any unit for line *A* out of service (assuming 4-per cent impedance mains) is 31.5 per cent on unit 21 (see curve 21, Fig. 5), and for line *D* out of service it is 27 per cent on unit 24 (see curve 24, Fig. 6).

Since many utility engineers follow the practise of

Table II—Calculated Results for Various Circuit Conditions in Fig. 7

Case No.	a	b	c	Ei	E_2	e_1	e_2	I_1	I_2	I_L	I_1'	I_2'
1	$0 + j6$	$5 + j0$	$95 + j31$	108.45	93.54	$100\angle{-3.08^\circ}$	$100\angle{0^\circ}$	1.67	1.077	0.957	0.575	0.432
2	$0 + j6$	$0 + j5$	$95 + j31$	102.29	100.00	$100\angle{-2.02^\circ}$	$100\angle{-1.10^\circ}$	0.70	0.321	0.985	0.637	0.348
3	$0 + j6$	$2.3 + j5.1$	$95 + j31$	103.00	99.20	$100\angle{-2.05^\circ}$	$100\angle{-1.01^\circ}$	0.779	0.324	0.964	0.633	0.335
4	$0 + j6$	$4.4 + j1.4$	$95 + j31$	105.73	96.27	$100\angle{-2.41^\circ}$	$100\angle{-0.681^\circ}$	1.690	0.653	0.958	0.585	0.408
5	$0 + j6$	$2.3 + j5.1$	$90 + j43.6$	103.60	99.25	$100\angle{-1.92^\circ}$	$100\angle{-0.947^\circ}$	0.820	0.303	0.959	0.630	0.334
6	$0 + j6$	$4.4 + j1.4$	$90 + j43.6$	106.19	96.48	$100\angle{-2.27^\circ}$	$100\angle{-0.642^\circ}$	1.225	0.616	0.957	0.584	0.407
7	$0 + j6$	$2.3 + j5.1$	$80 + j60$	104.32	99.35	$100\angle{-1.68^\circ}$	$100\angle{-0.830^\circ}$	0.679	0.265	9.952	0.625	0.331
8	$0 + j6$	$4.4 + j1.4$	$80 + j60$	106.69	96.87	$100\angle{-2.02^\circ}$	$100\angle{-0.568^\circ}$	1.260	0.548	0.958	0.585	0.408

The above data apply to Fig 7
Impedance and voltage values are in per cent
Current values are in times normal
Currents I_1 and I_2 occur with regulation and I_1' and I_2' are the corresponding currents without regulation
The network tie impedance ($2.3 + j5.1$) is that of one mile of standard 4/0 overhead line; and the time impedance, ($4.4 + j1.4$), is that of one mile of 1/0 under ground 3-conductor cable

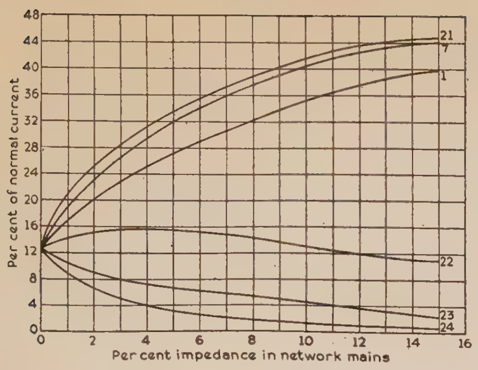
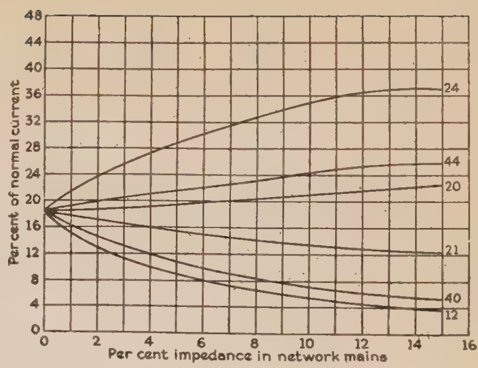


Fig. 5. Showing how the load normally carried by feeder *A* in Fig. 2 distributes among the units remaining in service when *A* is out

Transformer reactance 6 per cent. Percentage values 1,500-kva 4.3-kv base

Fig. 6. Showing how the load normally carried by feeder *D* in Fig. 2 distributes among the units remaining in service when *D* is out

Transformer reactance 6 per cent. Percentage values on 1,500-kva 4.3 kv base



allowing 25 per cent or more short-time overloads on substation transformers under emergency conditions, it appears that the feeder arrangement shown in Fig. 2 may not be objectionable from the point of view of overloads and it may be highly desirable from the point of view of economy. Naturally the overloads on any particular transformer on a network considerably smaller than the one in Fig. 2 are apt to be greater, and more reserve transformer capacity will need to be provided. However, it should be borne in mind that, for small networks, this problem of feeder arrangement is not important since each of the units in a small network will be supplied usually by a separate line.

Effect of Regulators on Emergency Load Division

The foregoing studies and accompanying charts are the result of calculating-board studies on fairly well designed networks. In addition to these operating characteristics under optimum conditions, the relative effects on network operation of certain irregularities in design are important. It is important to know under what conditions the automatic regulators on the network transformers affect the emergency load division, to know quantitatively what this effect may be, and to know how this effect varies with power factor, impedance of the 4-kv ties, etc.

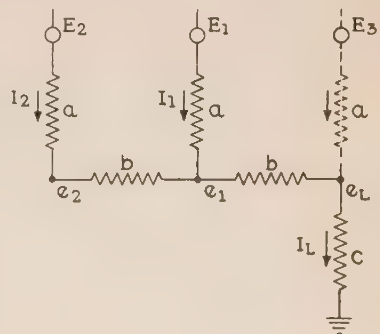
Voltage regulation on a primary network is maintained by means of automatic tap-changing equipment on the network transformer, or in some cases by means of induction regulators. In conjunction with a contact-making voltmeter and a line-drop compensator, these regulating equipments tend to hold 100 per cent voltage at some point in the secondary distribution system. The action of the regulator, in effect, is to change the magnitude of the voltage impressed on the transformer without affecting its phase angle. Furthermore, the operation of the contact-making voltmeter and compensator is to hold a constant magnitude of voltage at the load without regard to the angle of that voltage.

It is evident that this regulator action may in some cases influence the emergency load distribution in the network. The question may be asked, for example, if network unit 23 in Fig. 2 is taken out of service, what difference is there in the distribution of this load among the remaining units with and without automatic regulation? It may be shown (see below) that in closely linked well designed networks the load distribution is substantially the same with or without regulation. It may be shown further that the greater the inherent unbalance due to the inherent impedance characteristics of the network, the greater will be the effect of the automatic regulators to change the distribution. Thus, if feeder *C* in Fig. 1*A* is out, its load will divide uniformly between units 1 and 2 whether regulators and compensators are provided or not. Similarly the emergency load distribution in the large network shown in Fig. 2 will not change much if the units are unregulated.

In order to study the effect of regulator action on emergency load distribution it was necessary to go to an extreme case in which this action was accentuated. For this purpose the simple 3-unit network shown in elementary form in Fig. 7 was used. The impedance links *a* represent the network transformers and the connected transmission lines (the latter are usually negligible). The links *b* represent the 4-kv network mains or ties. (In this case only a single tie between units is used in order to simulate the most extreme case of a loosely linked network.) The links *c* represent 100 per cent loads. The problem is to determine how the load normally carried by unit 3 divides between units 1 and 2 when unit 3 is out of service. To simplify the analysis the loads carried by units 1 and 2 have been omitted since their effects may be superposed later if desired. The method used is the exact analytical one developed in the Appendix. The calculated results for the various circuit conditions studied are tabulated in Table II. To simplify the analysis it was assumed that voltage magnitude was held at the bus rather than at some point near the load. Since the loads themselves do

Fig. 7. Impedance diagram representing the simple 3-unit network studied to determine the fundamental effects of bus regulators on emergency load division

The distribution of load *C* between units 1 and 2 has been studied for various circuit constants; refer to Table II



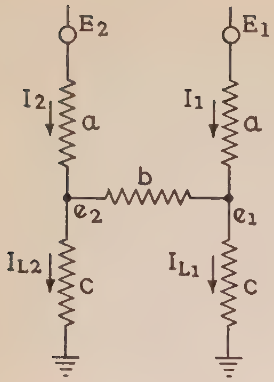


Fig. 8. Diagram representing the simple 2-unit network studied to determine the effect of bus regulators on a normally unbalanced load

not change this assumption is legitimate for the present purpose.

From the data of Table II the following pertinent facts may be observed:

1. For highly reactive network ties, such as overhead lines, the distribution of load 3 between units 1 and 2 is substantially the same with and without regulation. This fact apparently is equally true for all reasonable load power factors. Since the network studied is an extremely loosely linked one, it may be concluded from the above that the load distribution in all networks with overhead ties is not influenced greatly by the action of the regulators.

2. For highly resistive network ties, such as underground cables, the distribution of load 3 between units 1 and 2 is much more unbalanced with automatic regulation than without. This unbalance is less pronounced at lower load power factors.

3. The action of the regulator in cases 1, 4, 6, and 8 is to cause heavy circulating currents to flow from the adjacent unit to the remote unit as indicated by the magnitude of voltages E_1 and E_2. Since all of the "E" voltages are in phase, these circulating currents are highly reactive and the components of power current are relatively small. The actual division of power currents between units 1 and 2 is about the same with or without regulation.

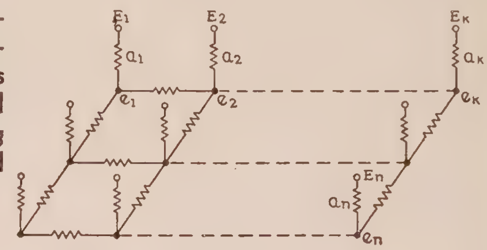
The above results demonstrate the maximum possible effect that regulation may have on load division. The network in Fig. 7, of course, would never be found in practice. The other extreme, from the standpoint of load division, is the 3-unit network shown in Fig. 1*A*. In this case uniform load division under emergency conditions always will obtain and the regulators will have no effect whatever.

The quantitative criterion that determines the manner in which a load at a given point in a network (i. e., the load on some transformer not in service) will distribute to the various points of feed is the range of variation in the transfer impedances from the point of load to the respective points of feed. A load at a given point will distribute directly as the transfer admittances to the various points of feed. In a closely linked network the variation in transfer admittance between one pair of feed points and any other pair of feed points is small, which means that a closely linked network insures a maximum uniformity in load division regardless of whether the network ties are cables or overhead lines. Furthermore, the differences in transfer admittances between feed points are less for a large network than for a small one (with the exception of certain symmetrical layouts), which indicates that a large network may have better operating characteristics from the standpoint of load division. It should be noted further that not only does the criterion of minimum differences in transfer admittances insure inherently a minimum of load unbalance, but this same criterion minimizes any tendency for the regulator action to set up circulating currents. To illustrate in a simple manner, refer to Fig. 7 and to case 4 in Table II. If the transfer admittances from the point of load e_L to the 2 sources, E_1 and E_2, had been equal, not only would I_1 and I_2 have been equal, but their circulating components would have been zero.

It may be stated in general that any effect which tends to improve load division under any emergency operating condition will also tend to limit circulating currents under the same condition.

The above conclusions are borne out in actual operating experience. In one particular case the transfer admittances between load points and various feed points do not differ by more than 10 per cent. Even though the network ties are highly resistive cables, the load carried by any transformer under normal conditions distributes practically uniformly when that transformer is out of service. The unit receiving the maximum portion of the redistributed load receives only 25 per cent more of this load than the unit receiving the minimum portion. Circulating currents are practicably negligible.

Fig. 9. Diagram representing the elements of the general network having *n* regulated feed points



Refer to the Appendix for the general analysis

Normal Network Operation

The foregoing analysis and discussion have been confined to the design and operation of the network as affected by emergency operating conditions. The following discussion is concerned with normal network operation.

Optimum network performance requires that:

1. The regulators function to maintain approximately 100 per cent voltage at some point in the secondary distribution system.

2. All circulating currents be reduced to a minimum.

3. The distribution of load in the network feeders be maintained as uniform as possible.

The chief instrument in operating the network to these requirements is the line-drop compensator. The following analysis will demonstrate how the compensator should be adjusted for various circuit constants to achieve these results.

Voltage Regulation

Consider a single network unit, which may be designated as unit k, at any point in a network. The circuit constants associated with this unit are related by the following equations, which, though approxi-

mate, are nevertheless quite accurate and well suited to the present purpose. These relations are sufficiently well known as to require no proof. They are not vector but algebraic relations.

$$E_k = e_b + a_k I_t \sin \theta_t \tag{1}$$

$$\beta = \frac{2I_t a_k \cos \theta_t}{e_b + E_k} \tag{2}$$

$$e_b = I_L (R \cos \theta_L + X \sin \theta_L) + 100 \tag{3}$$

$$e_{c.v.} = e_b - I_t (r \cos \theta_t - x \sin \theta_t) = 100 \tag{4}$$

where

E_k = voltage impressed on transformer k in per cent
e_b = network unit bus voltage and reference vector
β = angle in radians between E_k and e_b
a_k = transformer reactance in per cent
I_t = magnitude of transformer current in times normal
θ_t = power factor angle of I_t with respect to e_b
I_L = magnitude of load current in times normal
θ_L = power factor angle of I_L with respect to e_b. (Positive for lagging I_L and negative for leading I_L)
$e_{c.v.}$ = voltage impressed on contact-making voltmeter
r = resistance setting of the compensator
x = reactance setting of the compensator
R = apparent resistance in distribution system to load center
X = apparent reactance in distribution system to load center

The vector relations of the above quantities are shown diagrammatically in Fig. 11. If there is no circulating current, $I_t = I_L$. Otherwise $I_t = I_L + I_C$ (vectorially), where I_C is the circulating current from E_k into the network owing to any cause whatever. Since voltages at the load center should be ideally 100 per cent, and since $e_{c.v.}$ is likewise 100 per cent, the following algebraic equation expressing the condition of perfect network regulation follows from eqs 3 and 4 above:

$$(I_{CP} + I_{LP})\, r - (I_{CR} + I_{LR})\, x = I_{LP}R + I_{LR}X \tag{5}$$

where the added subscript P indicates power component of current, and the added subscript R indicates reactive component of current (both referred to e_b). In eq 5, the reactive components of current are positive or negative accordingly as they are lagging or leading. If for any reason the left-hand member of this equation is less than the right-hand member, the voltage at the load will be too low.

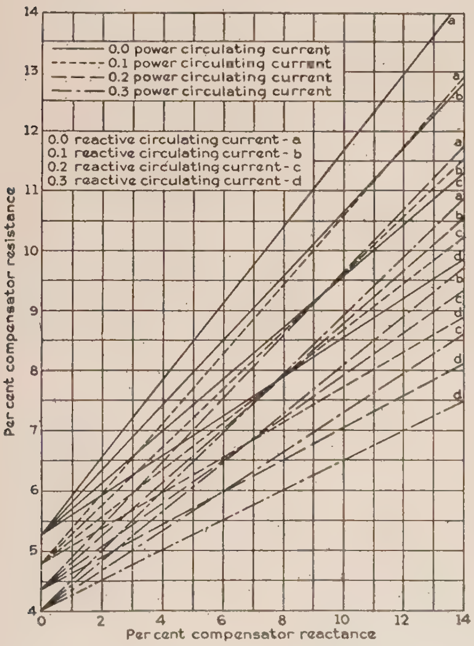


Fig. 10. Curves useful in determining the correct compensator settings to maintain good regulation on a primary network

Curves given for various amounts of power and reactive circulating current in the transformer. A 100-per cent 0.95-power factor load was assumed. Currents are in per unit values

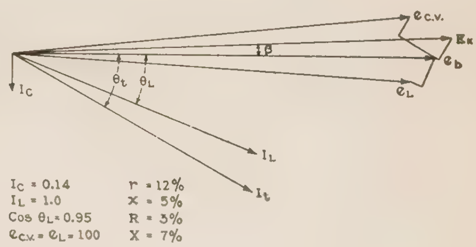
Equation 5 may be found particularly useful in determining the compensator setting best suited to good voltage regulation on the network. It is to be used on conjunction with eqs 6 to 9 given below. In Fig. 10 is a family of curves representing eq 5 for an assumed load current of 100 per cent, 0.95 power factor, and for R = 3 per cent and X = 7 per cent (all resistances and reactances being in per cent on a 1,500-kva 4.3-kv base). These load and circuit constants were chosen because they are fairly representative of a large number of cases.

As stated above, if eq 5 is satisfied by the compensator settings, good regulation will result. Note, however, that, if 100 per cent voltage is held at full load, the voltage at light load will be somewhat less than 100 per cent owing to the decreased power factor that inherently accompanies a light load condition.

Circulating Currents

In regard to the functions of the compensator, next in importance to voltage regulation is the limitation of circulating currents. As is well known and as is evident from eqs 4 and 5, this is accomplished by means of inverse reactance compensation. If any current flowing in the network unit transformer be resolved into power and reactive components, I_P and I_R, the effect of that current on bus voltage, by virtue of the compensator action, is to add rI_P and to subtract xI_R volts. The effects of all other components of voltage are negligible. That is, the reactance compensation is effective in changing transformer taps only when reactive current is flowing, and the resistance compensation is effective in changing transformer taps only when power current is flowing. Since load current usually is of high power factor, the over-compounding during peak loads is determined chiefly by the amount of resistance compensation. Also, since circulating currents usually are highly reactive, their suppression depends chiefly upon the amount of reactance compensation.

Fig. 11. Vector relations of the quantities defined in eqs 1 to 4



Both power circulating currents and reactive circulating currents are discussed below.

Circulating currents due to differences in tap positions of the network transformer regulators always are highly reactive. If transformer k has an impressed voltage n taps above or below the voltage level of the network, and if each tap gives an incre-

ment change in E_k of ΔE_k, the circulating current into the network will be:

$$I_{CR} = \Delta E_k D_{kk} n \tag{6}$$

where D_{kk} is the driving point admittance (reciprocal of driving point impedance) from transformer k into the network. Since D_{kk} is highly reactive, I_{CR} will be highly reactive and will tend to change the magnitude of e_b by the amount $\Delta E_k D_{kk} x n$ (a voltage increase if I_{CR} is leading and a decrease if I_{CR} is lagging). One tap change should not produce a change in bus voltage greater than the contact-making voltmeter voltage band in order that pumping and instability of the tap changers may be avoided, i. e.,

$$\Delta E_k D_{kk} x < \text{contact-making voltmeter band } (\pm 0.5 \text{ per cent}) \tag{7a}$$

Furthermore, 2 tap changes should produce a change in bus voltage greater than the contact-making voltmeter band to insure that reactive circulating currents shall be limited to a value not more than that corresponding to a single tap change, i. e.,

$$2\Delta E_k D_{kk} x > \text{contact-making voltmeter band} \tag{7b}$$

Unlike circulating reactive currents, circulating power currents usually are caused by phase-angle differences in impressed transmission voltages. If E_k is shifted δ deg from the voltage level of the network, the times normal circulating current will be

$$I_{CP} = 1.75\, D_{kk} \delta \text{ deg} \tag{8}$$

This current, being an in-phase power current, will tend to produce a voltage change in e_b of magnitude $1.75\, r D_{kk} \delta$ deg. This change in voltage impressed on the contact-making voltmeter will cause a tap change which in turn causes a reactive circulating current to flow. This reactive current will prevent more than a single tap change from occurring due to phase-angle differences provided

$$\Delta E_k D_{kk} x > 1.75\, D_{kk} r \delta \text{ deg} \tag{9}$$

The question arises as to how much circulating current owing to a difference in impressed-voltage phase-angle is permissible. This, of course, depends upon the degree to which the network transformers are loaded. In general, a circulating current of from 0.10 to 0.15 of normal load current should not be objectionable. Since D_{kk} varies from 0.12 in large networks to 0.065 in small networks (these values are the inverse of percentage driving point impedances, 1,500-kva 4-kv base), in the average network, assuming a permissible circulating current of 0.15 of normal, the allowable phase shift of E_k from the network voltage level should not be more than one degree.

Phase-angle differences in impressed voltages were determined on a particular network which is in operation. The maximum divergence from the average was found to be 0.98 deg at the time of full-load. The resulting power circulating currents were less than 0.10 of normal and not objectionable.

Problem

To illustrate the proper procedure in setting a network compensator, and to summarize the above analysis, the following example is given:

A network unit in a small sized network is supplied by a feeder whose voltage leads the network level by 0.5 deg. The driving point impedance from the transformer into the network is 9.2 per cent, or $D_{kk} = 1/9.2$. The contact-making voltmeter band is 1.0 per cent volts, and the regulator taps are 1.25 per cent volts each. What is the correct compensator setting?

From eq 8, the power circulating current due to 0.5-deg voltage phase displacement is 0.095 of normal. A reactive circulating current corresponding to one tap change (which is, from eq 6, 0.136 of normal in this case) should be assumed since the power circulating current is sufficient to cause at least one tap change. From eq 7*a* and 7*b* the compensator reactance x should be less than 7.35 per cent and greater than 3.63 per cent. For a first trial, let $x =$ 6 per cent. Then (assuming average circuit conditions, i. e., 0.95 power factor, $R = 3$ and $X = 7$) from eq 5 or from Fig. 10, the value of r is found to be 7.4 per cent, which value fails to satisfy eq 9. However, if $x = 5$ per cent, $r = 6.9$ per cent, which value satisfies eqs 5, 7, and 9 and is satisfactory.

Unbalanced Load

It is highly desirable that a network have characteristics such that a normally unbalanced load will distribute uniformly among the various points of feed. The natural impedance characteristics of a network promote uniform distribution of load whether the network be regulated or not. This fact is borne out in the calculating board studies illustrated in Figs. 3, 4, 5, and 6.

Table III—Circuit Constants and Calculated Data for Fig. 8

Quantity Measured	Case 1		Case 2	
a		$j6$		$j6$
b		$2.3 + j5.1$		$4.4 + j1.4$
c_1	1.1	$(95 + j31)$	1.1	$(95 + j31)$
c_2	0.9	$(95 + j31)$	0.9	$(95 + j31)$
E_1	101.68		101.08	
E_2	102.85		103.40	
e_1	100.0	$\angle -3.12°$	100.0	$\angle -3.04°$
e_2	100.0	$\angle -3.27°$	100.0	$\angle -3.35°$
I_1	0.952	$\angle -17.2°$	0.902	$\angle -11.4°$
I_2	1.063	$\angle -26.4°$	1.129	$\angle -30.2°$
I_1'	0.982	$\angle -20.8°$	0.996	$\angle -19.8°$
I_2'	1.028	$\angle -23.3°$	1.013	$\angle -23.8°$
I_{L1}	0.910	$\angle -18.2°$	0.910	$\angle -18.2°$
I_{L2}	1.100	$\angle -18.2°$	1.100	$\angle -18.2°$
I_L	2.010	$\angle -18.2°$	2.010	$\angle -18.2°$

The above data apply to Fig. 8. Impedance and voltage values are in per cent. Current values are in times normal. Currents I_1, I_2, and I_L occur with bus regulation, and currents I_1' and I_2' are the corresponding currents without regulation. The circuit constants are similar to those studied in Fig. 7 and Table II.

In order to study the problem of distribution of unbalanced loads, the simple 2-unit network shown in Fig. 8 was analyzed. The circuit constants and calculated data applying to this figure are summarized in Table III. It may be noted that 2 0.95-

power factor loads (load 1 being 10 per cent above normal and load 2 being 10 per cent below normal) were assumed. The distribution of loads was calculated assuming bus regulation (i. e., $e_1 = e_2 = 100$), and then assuming no regulation at all at the network busses (this latter case being equivalent to regulation at the generating station). The layout was studied assuming the network tie to be a highly reactive overhead line (case 1), and assuming it to be a highly resistive underground cable (case 2). An examination of the data in Table III will substantiate the following facts and conclusions.

The distribution of the load between the 2 network transformers is somewhat better without bus regulation than with, particularly so when the 4-kv tie is underground cable.

Thus, bus regulation alone, without compensation, cannot be said to improve load division. However, suppose that compensation of the type described above be incorporated in the network units of Fig. 8. In case 1 in which the network tie is a highly reactive overhead line, a power circulating current flows from unit 1 which is underloaded to unit 2 which is overloaded. This power circulating current helps to balance the load in the manner already indicated, but its effect on the compensator is to cause E_1 to increase and E_2 to decrease slightly, whereas the opposite effect is desired if a more equitable division of load is secured. Actually, the magnitude of the power circulating current in this case is so small that it would not result in any tap change at all.

Now consider case 2 in which the network tie is the highly resistive underground cable. Here the circulating current is highly reactive. This reactive current, in itself, has little effect in balancing the load. However, its action on the compensator, in contrast with the corresponding action of case 1, is to cause E_2 to increase and E_1 to decrease, which action has a beneficial effect in balancing the loads. It should be noted furthermore, that, whereas the circulating current in case 1 is small in magnitude, the circulating current in case 2 is of appreciable magnitude and will result in an actual change of taps.

The above analysis leads to the conclusion, then, that for networks inherently endowed with unbalanced loads, the resistance compensation should be somewhat smaller when the ties are overhead lines than when they are cables. Networks having overhead ties have a greater inherent tendency to balance loads than do networks with cable ties. Networks with cable ties, on the other hand, are able better to improve load division by virtue of the effect of the inverse reactance compensation.

Appendix—Analysis of the Regulated Network

A simplified impedance diagram of a primary network that is intended to represent any network having n points of feed is given in Fig. 9. The transformers feeding the grid are represented by impedances a_1, a_2, etc. These transformer impedance links are intended to include the impedances of the transmission lines feeding them, which, however, usually are negligible. The "E" voltages are the voltages impressed on the various transformers, and their magnitudes will vary from 100 per cent depending upon the tap positions of their respective load ratio control equipments. The "e" voltages are the bus voltages of the respective network units. It will be assumed here that the E voltages are all in phase, and that the e voltages are all equal in magnitude and equal to some value, say 100 per cent volts. Loads are not shown in Fig. 9 since the following analysis applies without respect to the manner in which the network is loaded.

The currents flowing into the general network of Fig. 9 at the various points of feed will be:

$$\begin{aligned} I_1 &= D_{11}E_1 + D_{12}E_2 + \ldots + D_{1n}E_n \\ I_2 &= D_{21}E_1 + D_{22}E_2 + \ldots + D_{2n}E_n \\ &\;\;\vdots \\ I_n &= D_{n1}E_1 + D_{n2}E_2 + \ldots + D_{nn}E_n \end{aligned} \qquad (10)$$

where D_{11}, $D_{22} \ldots D_{nn}$ are the driving point admittances from feed points 1, 2...n, respectively, and coefficients of the form D_{jk} are transfer admittances (between points j and k). These coefficients are the characteristic admittances of the network and may be determined readily by measurement or calculation. (See reference 6 at end of paper.)

In addition to eq 10 the following vector relations are evident:

$$\begin{aligned} e_1 + a_1I_1 &= E_1 \\ e_2 + a_2I_2 &= E_2 \\ &\;\;\vdots \\ e_n + a_nI_n &= E_n \end{aligned} \qquad (11)$$

In addition to eqs 10 and 11 the conditions of the problem specify that all of the E voltages are in phase but of unknown magnitude, and that all of the e voltages are equal to 100 per cent volts but of unknown phase angle.

If in eq 10 above, the jth equation be multiplied through by a_j, and the kth equation be multiplied through by a_k, and so on, and then if the term a_kI_k on the left of each equation be replaced by $E_k - e_k$, there results:

$$\begin{aligned} -e_1 &= (D_{11}a_1 - 1)E_1 + (D_{12}a_1)E_2 + \ldots + (D_{1n}a_1)E_n \\ -e_2 &= (D_{21}a_2)E_1 + (D_{22}a_2 - 1)E_2 + \ldots + (D_{2n}a_2)E_n \\ &\;\;\vdots \\ -e_n &= (D_{n1}a_n)E_1 + (D_{n2}a_n)E_2 + \ldots + (D_{nn}a_n - 1)E_n \end{aligned} \qquad (12)$$

Let eq 12 be written as:

$$\begin{aligned} D_{11}'E_1 + D_{12}'E_2 + \ldots D_{1n}'E_n &= e_1 \\ D_{21}'E_1 + D_{22}'E_2 + \ldots D_{2n}'E_n &= e_2 \\ &\;\;\vdots \\ D_{n1}'E_1 + D_{n2}'E_2 + \ldots D_{nn}'E_n &= e_n \end{aligned} \qquad (13)$$

Let the real and imaginary components of the D' coefficients be $D_{jk}' = m_{jk} + jn_{jk}$. Since all of the E voltages are in phase the following algebraic relations may be written:

$$\begin{aligned} m_{11}E_1 + m_{12}E_2 + \ldots + m_{1n}E_n &= R(e_1) \\ m_{21}E_1 + m_{22}E_2 + \ldots + m_{2n}E_n &= R(e_2) \\ &\;\;\vdots \\ m_{n1}E_1 + m_{n2}E_2 + \ldots + m_{nn}E_n &= R(e_n) \end{aligned} \qquad (14)$$

where $R(e_k)$ is the real part of e_k (using E as the reference vector). Since $e_k = E_k - a_kI_k$, and since a_kI_k is never greater than $0.07e_k$, it follows that $R(e_k)$ will differ from the magnitude of e_k by not more than $0.002e_k$, and it is therefore proper to replace the right-hand members of eq 14 by e. Equation 14 may be solved readily for the E voltages, by means of determinants or a simple calculating board set-up. Then the "I" currents may be determined from eq 10.

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Silicon Steel With A-C and D-C Excitation

Magnetic tests on silicon steel at 60 cycles with superposed d-c excitation are described in this article. The results, which are expressed in the form of curves, constitute an addition to existing data on this subject, and should be helpful to designers of apparatus in which combined alternating and direct magnetic fields exist.

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BOTH power transformers and instrument transformers may be subjected to d-c excitation in some applications. The d-c core-loss and excitation characteristics of the core material under such conditions are of importance, for they affect the rating of the power transformers and the accuracy of the instrument transformers. Combined alternating and direct magnetic fields are present also in other types of apparatus, affecting their performance by changing the characteristics of the magnetic circuits.

This article describes a series of a-c core-loss and excitation tests with superposed d-c excitation which recently were made on low-, medium-, and high-silicon sheet steel, and presents in detail the results for the first and third of these 3 materials. These tests constitute an addition to existing core-loss and excitation data (see bibliography) which will be helpful in designing apparatus where combined alternating and direct magnetic fields exist. They will assist also in predicting the performance of existing designs when subjected to similar conditions of magnetization. Both alternating and direct components of flux density were carried to high values, the maximum value of the sum of the 2 components being approximately 20,000 gausses. Corrections were made for distortion of the voltage wave form at high densities.

Briefly, the principal conclusions reached from the results of these tests are as follows:

1. In the range of alternating flux density below a certain value, which may be called the "critical" value, hysteresis loss tends first to rise, then to reach a maximum, and finally to decrease, as d-c excitation is superposed and the alternating component of flux density is held unchanged. Superposed d-c excitation decreases the hysteresis loss for any given alternating component of flux density in the range above the critical value.

2. The critical value of alternating flux density for silicon steel lies in the range 13,200 to 13,800 gausses (85 to 89 kilolines per sq in.).

3. The a-c excitation for any given alternating flux density is increased by superposed d-c excitation.

4. The d-c excitation for a given direct flux density in the low or moderate density range is decreased by a small amount of superposed a-c excitation, but is increased by larger amounts. The d-c excitation for a given direct flux density in the high density range is increased by superposed a-c excitation.

Diagrams of Fig. 1 illustrate the change in the cycle of magnetization that is caused by a direct component of exciting current. The flux wave and the corresponding hysteresis loop are shifted from their symmetrical positions by a direct component of flux density. The shape of the hysteresis loop is changed; in general, its area, which represents the hysteresis loss per cycle, also is changed, although the amplitude of pulsation (vertical length) remains the same.

Eddy current loss, being a function of the effective value of the induced voltage, is not affected by the direct component of flux density, if, as assumed in Fig. 1, the amplitude and form of the flux and voltage waves remain unchanged. The assumption regarding the form of the voltage wave, however, is only approximately correct. Changes in the exciting current wave form and amplitude will react upon the impedance in the magnetizing circuit to distort the wave form of the induced voltage, so that the eddy current loss will be changed somewhat.

The change in the exciting current is associated with the change in the shape of the hysteresis loop. The general slope of the loop is decreased, so that the same pulsation of flux density (vertical length) requires a much greater pulsation of exciting current (horizontal length). Thus, in Fig. 1, the amplitude of the exciting current pulsation (x_2, x_1) is much greater for the displaced than for the symmetrical flux wave, although the amplitude of flux pulsation (a_2, a_1) is the same for both. There is, of course, a small component of exciting current due to eddy current loss, which is neglected in Fig. 1.

The converse effect, that of superposed a-c excitation on d-c excitation is illustrated by the diagrams of Fig. 2. The 2 flux waves have the same direct components of flux density (d_1, d_2) but different alternating components (a_1, a_2). The direct components of exciting current (y_1, y_2) are quite different.

Changes in the shape of the hysteresis loop illustrated in Figs. 1 and 2, have been shown in detail previously by other investigators (see bibliography).

Methods of Test

Tests were made on 20-lb laminated ring samples 9.45 in. outside diameter by 6.3 in. inside diameter.

Full text of "Loss Characteristics of Silicon Steel at 60 Cycles With D-C Excitation" (No. 33-54) presented at the A.I.E.E. North Eastern District meeting, Schenectady, N. Y., May 10–12, 1933.

The rings were wound with uniformly distributed primary and secondary windings of 200 turns each, the primary being outside of the secondary.

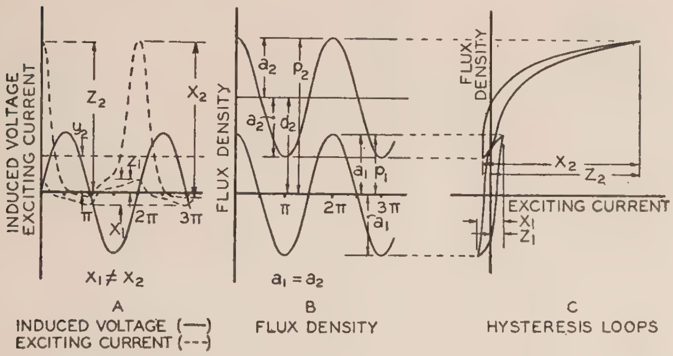
Apparatus and circuits used are shown in Fig. 3, which makes clear the method of supplying the combined alternating and direct current to the primary winding of the sample. The core loss was measured with an astatic reflecting dynamometer wattmeter. The secondary voltage was measured with both a flux voltmeter[8,9] (for all numbered references see bibliography) reading average rectified voltage times 1.111, and an rms voltmeter, thus allowing both the alternating flux density and the secondary copper loss to be determined correctly for a distorted voltage wave form. The use of the 2 voltmeters also allowed the eddy current loss to be corrected for a distorted voltage wave form, in separating the 2 components of the total core loss.

The direct flux density was measured with an over-damped ballistic galvanometer connected to a single-turn coil on the sample, deflections being read as the direct current was reversed. Several reversals were made each time before recording the deflection. A high-reactance choke coil was connected in series with the galvanometer to insure negligible alternating current and negligible loss in that circuit. The galvanometer was calibrated by means of a standard mutual inductor, and its sensitivity was adjusted by a shunt resistance.

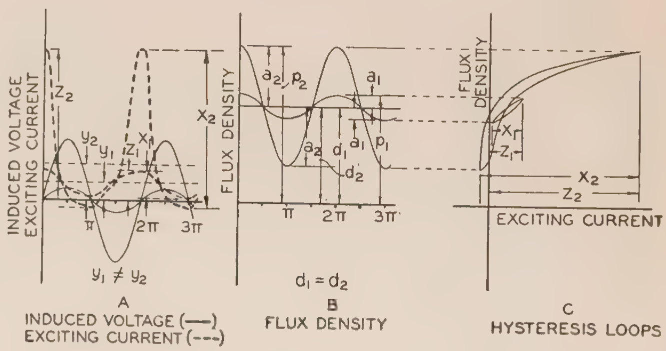
In making the tests, the flux voltmeter reading, and consequently the alternating flux density, was held constant at each desired value while the direct current was varied in steps over as great a range as the current carrying capacity of the primary winding permitted. The sample was demagnetized each time before proceeding to the next value of alternating flux density. Considerable time was allowed between readings with no power on, in order to minimize heating of the sample and consequent error in the calculation of the eddy current loss.

In separating the total core loss into hysteresis and eddy current components, the percentage of eddy current loss with no d-c excitation was taken from the results of numerous separation tests previously made on the same material, and it was assumed that the eddy current loss was not affected by superposed d-c excitation except as the voltage wave form was changed. At high densities, where a difference in the readings of the 2 voltmeters indicated a distortion of the voltage wave form, the calculated eddy current component was multiplied by the square of the ratio of the rms voltage to the flux voltmeter voltage before subtracting it from the total core loss. This correction was necessary because the calculated eddy current loss was for a sine wave form of voltage, and therefore somewhat less than that actually existing with the distorted voltage wave.

Excitation tests were made in a similar manner, except that the total rms current and the direct current were measured, instead of the power in watts. An rms ammeter and a d-c ammeter were connected in series with the primary winding, and the wattmeter and the rms voltmeter were switched out of



Subscript 1 refers to conditions with no d-c excitation
Subscript 2 refers to conditions with d-c excitation



Subscript 1 refers to conditions with a small flux pulsation
Subscript 2 refers to conditions with a large flux pulsation

Figs. 1 (left) and 2 (right). Wave forms of induced voltage, flux density, and exciting current, with corresponding hysteresis loops showing (left) the effect of superposed d-c excitation and (right) the effect of varying flux pulsation on the direct component of excitation

- a Alternating flux density (1/2 total pulsation)
- d Direct flux density (average over a complete cycle)
- p Peak flux density (maximum in each cycle)
- x Amplitude of exciting current pulsation
- y Direct component of exciting current (average current)
- z Peak value of exciting current

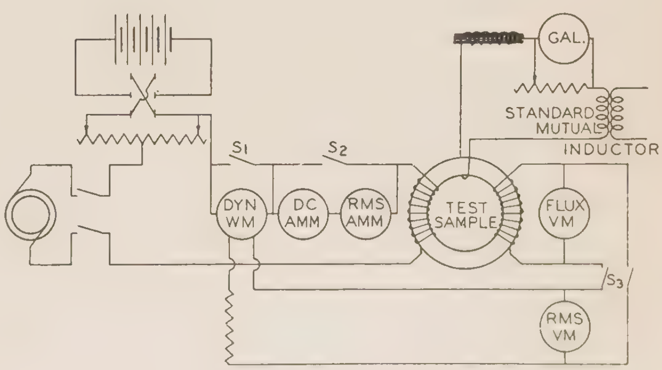
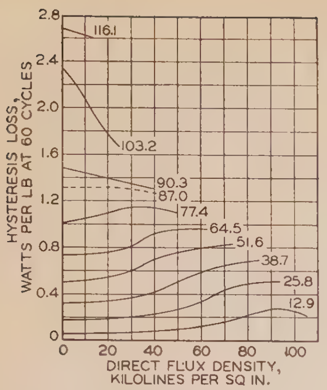
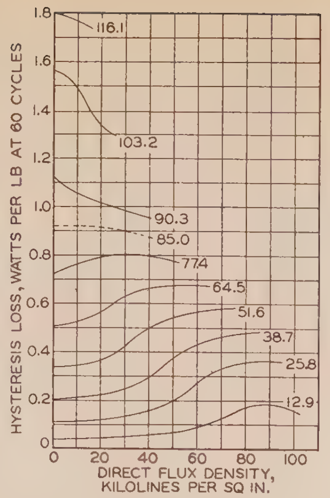


Fig. 3. Circuit diagram for core loss and excitation tests with superposed d-c excitation

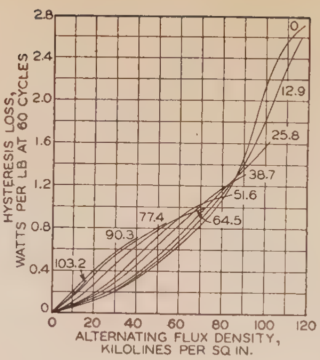
Core loss. S_1 open; S_2, S_3 closed
Excitation S_1 closed; S_2, S_3 open



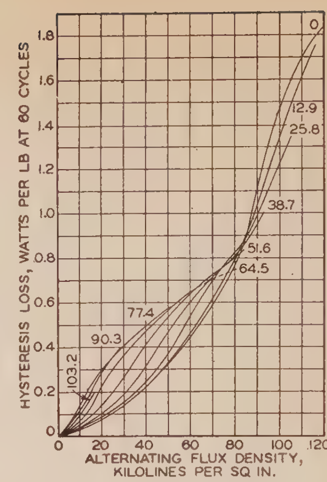
Figures on curves represent direct flux density in kilolines per sq in.



Figs. 4 and 5. Hysteresis loss vs. direct flux density with various alternating flux densities, for (left) low-silicon steel and (right) high-silicon steel



Figures on curves represent alternating flux density in kilolines per sq in.



Figs. 6 and 7. Hysteresis loss vs. alternating flux density with various direct flux densities, for (left) low-silicon steel and (right) high-silicon steel

the circuit. The a-c component of exciting current was determined from the equation

$$I_{a-c} = \sqrt{I_{total}^2 - I_{d-c}^2}$$

The silicon contents of the 3 grades of material tested were approximately $2^1/_2$, $3^1/_4$, and 4 per cent for the low-, medium-, and high-silicon steels, respectively. Each material was annealed before the samples were punched out. The low-silicon sample was punched from sheets 0.019 in. thick; the medium- and high-silicon samples, from sheets 0.014 in. thick.

Results

Results are presented graphically in Figs. 4 to 11, inclusive. Only the hysteresis component of core loss is given. Alternating flux density values refer to half the amplitude of flux pulsation, and direct flux density values to the average flux density over a complete cycle; a-c excitation values refer to the effective value of the alternating component, and d-c excitation values to the average current over a complete cycle.

The alternating flux density ranged from zero to 18,000 gausses (116.1 kilolines per sq in.) and the direct flux density from zero to 15,600 gausses (100 kilolines per sq in.) the highest value of the sum of the 2 components being approximately 20,000 gausses (129 kilolines per sq in.).

Throughout the range of flux density for which the solid-line a-c excitation curves of Figs. 8 and 9 are plotted, the form factor of the induced voltage did not vary from 1.111 by more than 1 per cent. For the dotted-line curves of Figs. 8 and 9, with the exception of the 2 uppermost curves, the form factor of the induced voltage wave did not vary from 1.111 by more than 4 per cent; and for the 2 uppermost dotted-line curves it did not vary from 1.111 by more than 9 per cent.

Curves for the medium-silicon steel (not included in this article) were similar in form to those for the other 2 grades.

Hysteresis Loss

Inspection of the curves of Figs. 4 and 5 shows that for alternating flux densities of 14,000 gausses (90.3 kilolines per sq in.) and greater, the hysteresis loss tends to decrease immediately as direct flux density is superposed; for alternating flux densities of 12,000 gausses (77.4 kilolines per sq in.) and less it tends first to increase to a maximum, and then to decrease. For these lower densities, the hysteresis loss did not fall below the value without superposed direct flux density. However, the final slopes of some of the curves (Figs. 4 and 5) indicate that such a reduction might occur if the direct flux density were carried high enough.

In the range between the 2 densities given in the preceding paragraph, there is an alternating flux density for which the initial tendency of the hysteresis loss is neither to increase nor to decrease. It may be called the "critical" value. For the low-, medium-, and high-silicon steels the critical values are approximately 13,500, 13,800, and 13,200 gausses (87, 89, 85 kilolines per sq in.), respectively. Two of these are illustrated by the dotted-line curves in Figs. 4 and 5. Values for the dotted-line curves were read from the curves of Figs. 6 and 7, the critical alternating flux density being approximately the density at which the curve for no direct flux density intersects that for 2,000 gausses (12.9 kilolines per sq in.).

Table 4 of a previous paper[2] by Holm shows a critical value of 13,450 gausses (86.7 kilolines per sq in.) for motor sheet steel. Table I of a paper by Chubb and Spooner[4] indicates a critical value of approximately 10,300 gausses (66.5 kilolines per sq in.) for silicon steel. Apparently none of the other investigators referred to carried the alternating component of flux density high enough to determine the critical value.

The critical value indicated by the tests of Chubb and Spooner is considerably lower than the others, all of which are nearly alike. Possibly this may be accounted for, at least in part, by the fact that the tests by Chubb and Spooner were made on a trans-

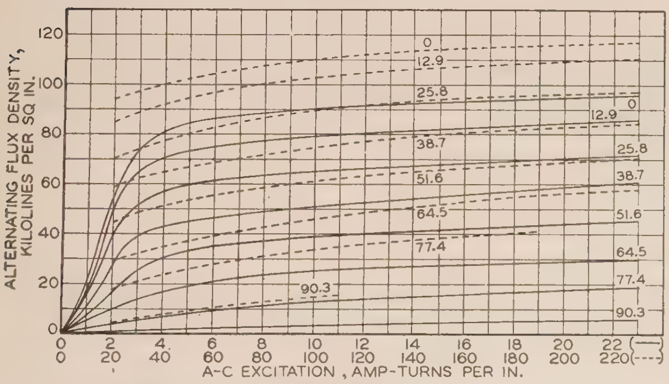
former rather than on a ring sample as were the present tests and those made by Holm.

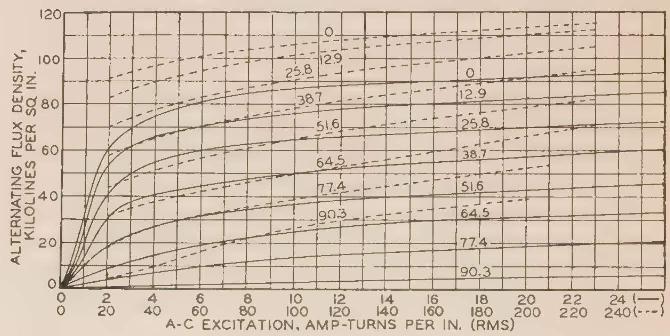
These results may be used also to calculate approximately the hysteresis loss when alternating flux waves of 2 different frequencies are combined to form a flux wave with pulsations. The loss for each cycle of the pulsation during one low frequency cycle is found by taking an alternating flux density equal to half the amplitude of the pulsation and a direct flux density equal to the mean value of flux density during the pulsation. The losses for all the pulsations in one low frequency cycle then are added to give the pulsation loss per cycle. The symmetrical hysteresis loss for an alternating flux density equal to the maximum flux density during the cycle then is added to give the total hysteresis loss per low frequency cycle. This procedure assumes that the area of the minor hysteresis loops traced by the pulsations of flux is approximately the same as that of the minor loops of the same flux density range which have been repeated many times with a constant displacement, and that the area is the same whether the upper tips of the minor loops be on the normal induction curve or on the boundary of a large symmetrical loop. A previous paper by Spooner[5] shows that these are approximately true although the first minor loop is somewhat larger than succeeding ones, and the area varies slightly with horizontal displacement of the loop even though the vertical displacement is constant. The minor loops also may affect slightly the area of the symmetrical loop. Unfortunately, no data appear to be available to determine the extent of this effect.

Excitation

The first group of excitation curves (Figs. 8 and 9) shows that for any given alternating flux density superposed d-c excitation increases the required a-c excitation. The solid-line curves of Figs. 8 and 9 represent the rms excitation corresponding to a sine wave of induced voltage, since, for the range they cover, the form factor of the induced voltage was within 1 per cent of 1.111. The values of excitation given in the dotted-line curves, for which the wave form became somewhat distorted, are higher than would have been obtained with a sinusoidal voltage wave.

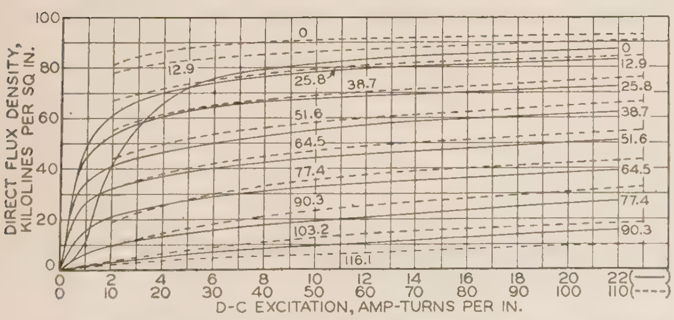
The second group of excitation curves (Figs. 10 and 11) shows the effect of superposed a-c excitation on direct flux density and d-c excitation. In the range from zero to 11,200 gausses (72 kilolines per sq in.) approximately, depending on the material, the direct flux density for a given value of d-c excitation is somewhat increased by small amounts of superposed alternating flux density; larger amounts decrease it. Neither the exact extent of the direct flux density range nor the value of the alternating component giving the greatest increase of direct flux density could be determined because of lack of data for alternating flux densities between zero and 2,000 gausses (12.9 kilolines per sq in.). Direct flux densi-

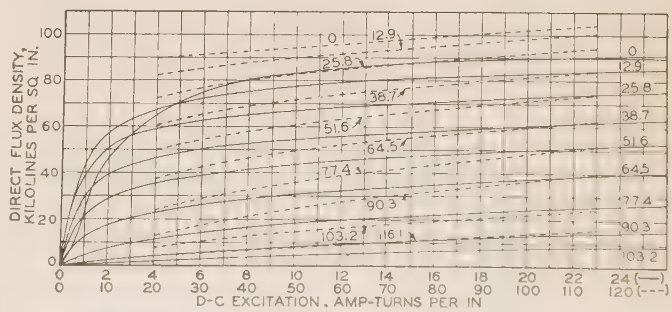




Figures on curves represent direct flux density in kilolines per sq in.

Figs. 8 and 9. Alternating flux density vs. a-c excitation with various direct flux densities, for (left) low-silicon steel and (right) high-silicon steel





Figs. 10 and 11. Direct flux density vs. d-c excitation with various alternating flux densities, for (left) low-silicon steel and (right) high-silicon steel

Figures on curves represent alternating flux density in kilolines per sq in

ties above this range are not increased at all by superposed a-c excitation, but are decreased immediately.

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A New High Speed Air Circuit Breaker

The range of the high speed air circuit breaker has been extended to a 10,000-amp 750-volt d-c continuous rating. It is particularly adaptable to railway systems, and in this larger rating, a single unit has ample capacity for the largest size conversion units now available for 600-volt service. A description of the new circuit breaker is given in this article.

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A HIGH SPEED air circuit breaker of high capacity in a single unit was made desirable by recent developments in railway systems. Among these factors was the decision of the board of transportation of the city of New York to install power conversion units of 3,000 kw and 4,000 kw rating on the Eighth Avenue Subway project in that city. A comparable rating in a single unit circuit breaker was desired. The previous maximum rating of high speed circuit breakers had been 4,000 amp and although for higher machine ratings a few installations had been made with 2 to 3 circuit breakers in parallel, the number of conversion units to be installed on the New York City system made the development of a larger single breaker unit desirable.

Especially prepared for ELECTRICAL ENGINEERING. *Not published in pamphlet form.*

The new circuit breaker, known as type *JR-36* and illustrated in Figs. 1 and 2, is rated 750 volts direct current, 10,000 amp, continuously. This rating provides ample capacity for the largest size conversion units available at present for 600-volt railway service.

INTERRUPTING CAPACITY

Since the high speed circuit breaker limits the current peak to a fraction of the theoretical sustained value which the short circuit would reach if not opened, it has been customary to specify interrupting capacity in terms of initial rate of current rise, theoretical sustained value of current (or an equivalent total resistance of the short circuit external to the conversion unit), and time from tripping point to actual maximum current as limited by the operation of the high speed circuit breaker.

With the new high speed circuit breaker, the peak of the short-circuit current will occur in 0.007 sec on a short circuit having an initial rate of rise of 14×10^6 amp per sec and a theoretical sustained value of 200,000 amp. Time is measured from tripping point to maximum current. A typical oscillogram of a short circuit on a 625-volt 4,000-kw 60-cycle synchronous converter protected by the new high speed breaker is reproduced in Fig. 3. The external circuit resistance is 0.000694 ohm. The initial rate of rise is approximately 5.75×10^6 amp per sec.

GENERAL DESCRIPTION

The present day practice of truck mounted interchangeable units made a compact design especially desirable. The supports are on 20 x 25 in. centers. The over-all dimensions of 24 x $57^3/_8$ x 48 in. are well adapted to truck mounting.

The welded frame is fabricated entirely from bar and plate stock with machined surfaces to receive the subassemblies. The frame is at the potential of the moving contact assembly and is insulated from the mounting subframe by 4 molded insulators.

MAIN CIRCUIT ELEMENTS

Because of the high continuous rating especial care was taken to keep the current carrying parts to minimum length. This was accomplished by mounting the 2 $4^1/_2$x$4^1/_2$ in. positive terminal bars directly over the corresponding negative bars. This arrangement makes possible relatively short flexible shunts as the bridging member of the circuit. The moving contacts are made an integral part of the shunt ends and thus only 2 bolted connections are made in the main current carrying circuit of the

breaker; i. e., shunts to lower bars and stationary contact member to the upper bars. The loop arrangement also increases the mechanical speed of opening on very heavy short circuit currents due to the electromagnetic force exerted on the contact arms which is in the direction to accelerate the contacts toward the fully open position.

The contact arms are fabricated from duralumin. The midpoints of the arms are connected by pull links of the same material to the main armature lever. Very light moving parts are essential if high mechanical speed is to be obtained without excessive accelerating forces. The lower ends of the arms are carried by bell cranks to which are attached the contact pressure springs. The outer ends of the bell cranks are provided with rollers bearing on the cross head of the hydraulic reset piston.

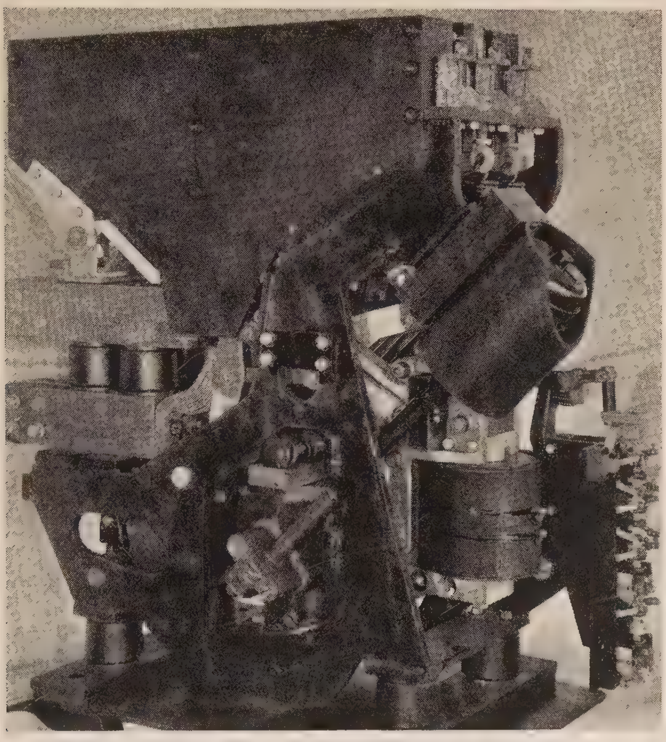


Fig. 1. The new high speed high capacity air circuit breaker equipped for relay tripping

When separate relay tripping is used the negative bus connection is made directly to the lower bars. For inherent tripping the shunts for the twin series tripping coils are made an integral part of the lower bars with the outer shunt castings arranged for bus bar connection.

The leverage arrangement used is shown schematically in Fig. 4. The lift of the hydraulic piston during reclosure rotates the moving contact arms in a clockwise direction about the bumper A as a fulcrum until the holding magnet armature is closed. The retraction of the piston then allows the contact arms to rotate in a counter clockwise direction and close the circuit. This mechanism is completely trip free. Tip wear does not alter the main opening spring tension and consequently does not affect the calibration.

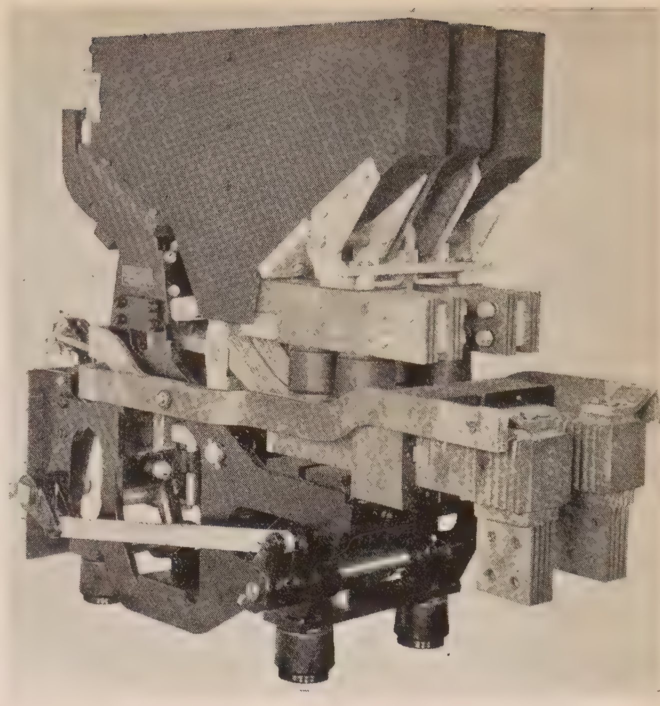


Fig. 2. The new high speed high capacity air circuit breaker equipped with inherent tripping

The 4 main contacts and 1 auxiliary arcing contact are carried on separate arms with separate contact pressure springs. The auxiliary contact arm is provided with a simple lost motion arrangement so as to make before and break after the main contacts. All arcing is confined to this auxiliary contact which is provided with renewable stationary and moving contact tips. The 4 main contacts are silver faced to obtain a low contact resistance and insure proper equalization to current division.

Reset Mechanism

Motor operation of the mechanism allows a lower demand on the operating battery than the solenoid type mechanism used on the smaller size circuit breakers. An entirely new type mechanism, based upon the use of hydraulic transmission, allows a mechanically simpler and more compact arrangement than any other mechanical arrangement heretofore used. The component parts, however, are conventional, standard devices which introduce no new or untried functions.

The driving motor is direct connected to a gear oil pump mounted at the side of the hydraulic cylinder. The motor drives through an insulated shaft and is mounted on an insulating base, and shielded from the main circuit breaker frame.

An automatic by-pass release valve is incorporated in the cylinder casting. This valve is held closed by pump pressure during the up stroke of the piston. When the hydraulic pump is stopped at the top of the stroke, pressure is released from this valve which opens, connecting the upper and lower ends of the cylinder and allowing the piston to return to the bottom position. The reclosing cycle is completed in approximately 4 sec.

Holding and Tripping Mechanism

The holding mechanism consists of a laminated armature carried on an armature lever fabricated from duralumin to which are attached the main opening springs. The armature spans the laminated pole tips of the d-c excited holding magnet.

Tripping is effected by the well-known flux shifting principle which allows an instantaneous release of the armature when current in the tripping coil, located between the pole tips, has reached the tripping value.

For polarized tripping on overcurrent or reverse current only, inherent trip is provided. In this case the tripping coil consists of 2 series single-turn coils each energized from separate shunts incorporated in the negative bus bars as previously described.

Checking calibration, after installation, on devices tripped directly by line currents of large magnitude has usually been difficult if at all feasible. A special low voltage calibrating coil has been included as a part of the series tripping coil assembly and is calibrated for each calibrated point of the series coil. A 12-volt automotive type storage battery, a small rheostat, and a direct reading ammeter constitute the only test apparatus needed to check the actual tripping point at any calibrated setting.

The excitation of the d-c holding magnet may be from any constant potential source. For machine breakers the excitation is usually taken from the machine bus. The effect of variable excitation on tripping point is shown in Fig. 5.

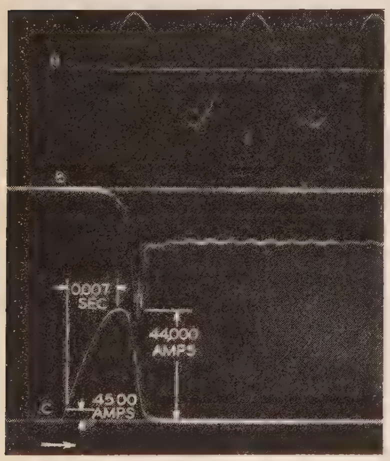


Fig. 3. Short circuit on a 625-volt 4,000-kw 60-cycle synchronous converter protected by the new high speed circuit breaker with inherent tripping set to trip at 4,500 amp

Curve *A*. 60-cycle timing wave
Curve *B*. Voltage across circuit breaker
Curve *C*. Current through circuit breaker

Discrimination

Reduction of tripping point on high rates of rise, by control of the ratio of inductance of the shunts to inductance of the series tripping coils, is obtained by the use of laminations on shunts and tripping coil leads. This arrangement gives the so-called discriminating effect whereby the effective tripping point is lowered under short-circuit conditions.

For machine reverse current protection a low tripping point is desirable since the maximum reverse fault current can be limited to a lower value. The polarized inherent tripping lends itself to a low tripping setting because it is inoperative on normal load current. Under this condition discrimination is not essential because the setting is independent of load current. On the form of circuit breaker with inherent tripping a minimum setting of 20 per cent of continuous rating may be obtained. This may be compared with previous practice of a minimum setting of 60 to 75 per cent.

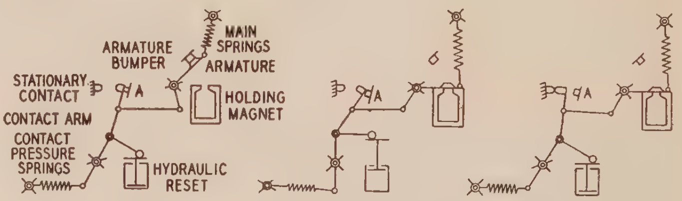


Fig. 4. Steps in the reclosing cycle of the new high speed circuit breaker, showing trip free operation

1. Open position
2. Armature closed, ready to trip. Contacts still fully open
3. Reset mechanism retracted. Contacts fully closed

With a very low tripping point for reverse current it becomes essential to provide no discrimination or a very small amount. Under steady state conditions the current divides between the series tripping coil and its shunt inversely as their respective resistances. Under transient conditions the division of current between the series tripping coil and its shunt is dependent upon both the inductance and resistance of the tripping coil and shunt. To maintain the same division of current under transient conditions as under steady state conditions the ratio of the inductances must equal numerically the ratio of the resistances of the parallel tripping coil and shunt. This may be indicated as follows (see Fig. 6):

Let

L_1 = inductance of trip coil
L_2 = inductance of shunt
R_1 = resistance of trip coil
R_2 = resistance of shunt

For all conditions the premise may be stated that

$$\frac{I_1}{I_2} = \frac{R_2}{R_1} \tag{1}$$

or

$$I_1R_1 = I_2R_2 \tag{2}$$

There may also be written

$$I_1R_1 + L_1\frac{dI_1}{dt} = I_2R_2 + L_2\frac{dI_2}{dt} \tag{3}$$

From eq 2

$$R_1\frac{dI_1}{dt} = R_2\frac{dI_2}{dt} \tag{4}$$

or

$$\frac{\frac{dI_1}{dt}}{\frac{dI_2}{dt}} = \frac{R_2}{R_1} \tag{4a}$$

Subtracting eq 2 from eq 3 and rearranging terms there results

$$\frac{L_2}{L_1} = \frac{\frac{dI_1}{dt}}{\frac{dI_2}{dt}} \tag{5}$$

Or, equating eq 4*a* and eq 5

$$\frac{L_2}{L_1} = \frac{R_2}{R_1} \tag{6}$$

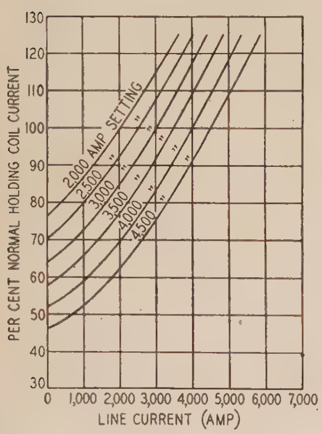
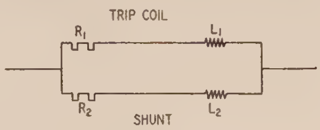


Fig. 5 (left). Characteristic curves showing effect of control voltage variations on tripping point

Fig. 6 (below). Diagram of tripping coil and shunt circuit



Accurate inductance values may best be obtained by calculation from oscillographic records of current rate of rise by the relation

$$L = \frac{E}{di/dt}$$

Where

E = applied voltage

$\frac{di}{dt}$ = initial rate of current rise in amperes per second

Where discrimination is desired the current in the tripping coil may be calculated from equations taking into account the external circuit inductance and resistance (see "High Speed Circuit Breaker in Railway Feeder Networks" by J. W. McNairy, Trans. A.I.E.E., v. 45, 1926, p. 962–9).

High Speed Relay Tripping

For tripping on both overcurrent and reverse current the tripping coil is energized from the d-c control battery by the contacts of high speed relays arranged to trip from a separate shunt in the main circuit. This arrangement has not been used heretofore on d-c high speed circuit breakers and is only feasible now through the use of high speed relays developed for this purpose.

Each relay is in effect a miniature high speed circuit breaker tripping on the flux shifting principle. Reduction of tripping point by inductance ratio control is obtained in a similar manner. Discrimination may be separately controlled for each relay.

Due to the very small and light moving parts of the relay, very high speed contact closing operation is obtained and the over-all breaker rupturing time is not appreciably increased. An oscillogram of a short circuit on a 625-volt 3,000-kw 60-cycle synchronous converter protected by one of these high speed breakers equipped with relay trip is shown in Fig. 7. The external circuit resistance was 0.000562 ohm.

Blowout and Arc Chute Arrangement

To obtain high speed operation, fast arc rupturing is just as essential as quick release and high speed of the operating mechanism. A knowledge of the behavior and methods of control of the gas pressures generated during the arc rupturing process becomes of prime importance in opening the high currents encountered under maximum short-circuit conditions with high substation capacity. With intelligent direction this characteristic can be converted from a potential liability to a decided asset, and these forces utilized for rupturing by forcing the arc out into the chute at a higher rate than would be possible with the blowout magnet alone.

The main blowout magnet is energized by a semi-detached blowout coil which is inserted in the circuit, at the instant the arcing tips part, by transfer of the arc from the stationary contact face to the arcing horn. This arrangement facilitates the transfer of current to the arcing contact from the paralleled main contacts, without sacrifice of blowout effectiveness, by minimizing the change in inductance in the internal breaker circuits. A fully detached auxiliary blowout magnet, located in the upper part of the chute, is inserted in the circuit as the arc is forced upward.

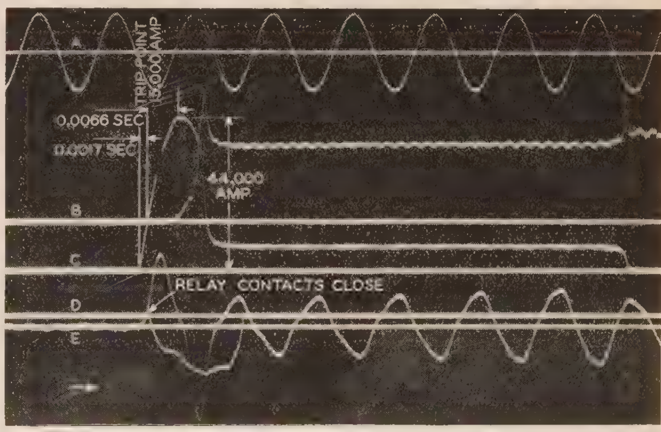


Fig. 7. Short circuit on 625-volt 3,000-kw 60-cycle synchronous converter protected by the new high speed circuit breaker with relay tripping

Curve *A*. 60-cycle timing wave
Curve *B*. Voltage across circuit breaker
Curve *C*. Current through circuit breaker
Curve *D*. Circuit breaker tripping current
Curve *E*. Converter input, alternating current

The main arcing horns which act as the electrodes after the arc has been drawn and transferred, are made of a special non-magnetic nickel iron alloy having high specific resistance (150 microhms per cubic cm) and low permeability (approximately that of air). For the severe rupturing duty to which the high speed circuit breaker is subjected this material is well adapted and in comparison with the alloy

castings used under less severe conditions offers the advantages of reduction of energy in the arc stream and greater resistance to burning. The voltage drop in the main arcing horns may be 10 per cent or more of the total voltage across the contacts under maximum short circuit conditions.

Energy Consumption on Street Railways

Energy consumption on a street railway is affected by several variable factors; but because of their interrelation, it has been difficult to determine the separate effect of any one of these variables. A prolonged and detailed study on the railway property of the St. Louis (Mo.) Public Service Company, however, has resulted in the determination of relationships between energy consumption and weather conditions, passenger loading, and speed.

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ON ANY STREET RAILWAY operating under the same conditions of track layout, topography, and geographic location, and with the same equipment, the energy consumption per car mile of the system operated will vary with: (1) weather conditions; (2) number of passengers carried; (3) schedule speed operated; (4) density of vehicular traffic on the streets; (5) mechanical condition of the equipment; and (6) efficiency of operation of the motorman. Because of the interrelation of these variables, it has been difficult to separate the variation of energy consumption with each. It has been possible on several railways, however, to segregate some of these variables and to determine their relationships with the energy consumption. A prolonged and detailed study on the railway property on the St. Louis (Mo.) Public Service Company resulted in the determination of relationships between energy consumption and weather conditions, passenger loading, and speed.

Full text of a paper recommended for publication by the A.I.E.E. committee on transportation. Manuscript submitted Jan. 30, 1932; released for publication Sept. 11, 1933. *Not published in pamphlet form.*

It has been found that variations in the mean monthly temperature, used as a measure of the weather conditions, causes the energy consumption to increase as much as 10 to 15 per cent in midwinter over midsummer, when the cars have no electrical heating in them; and as much as 50 per cent increase when the cars are heated electrically. For each increase of 1 per cent in passengers carried, the energy increases 0.75 per cent; and for each 1 percent increase in scheduled speed (system average), the energy consumption increases 1.8 per cent. The methods used in deriving these figures are explained in detail, and the figures have been checked on other street railways.

Although the effects of the weather conditions, the number of passengers carried, the scheduled speed and the efficiency of operation of the motormen have been evaluated, it has been impossible accurately to show the effect of vehicular traffic on the streets. The effect of the mechanical condition of the equipment can be, and has been, shown for individual cars; but no evaluation has been made for a system as a whole, although it is patent that the better the operating conditions of the cars, the lower the energy consumption. The variation of the power demand is similar to the variation in energy consumption, but not by as great an amount.

Method of Procedure

Relationships given in this paper, deal with the energy consumption for a metropolitan street railway as a whole, not for individual cars. Practically all large systems operate cars of different types, weights, and motor equipments, on various lines or routes that have different characteristics. It is impossible in many cases to segregate the energy consumption by lines, and often to obtain quantitative values for the variables. The characteristics of an individual line vary and change much more rapidly than for the system as a whole, and the figures for the latter are more reliable and of more general usefulness.

The basic data upon which the information in this paper rests were obtained by the author in working on methods of reduction of energy consumption on the system of the St. Louis Public Service Company, St. Louis, Mo. This company operates about 1,500 cars over 460 miles of single track. The relationships have been checked by information obtained on other similar street railways in various localities in the northeastern part of the United States and are believed to be reliable and reasonably accurate. No claim for absolute accuracy is advanced because of the methods used and the insufficiency of the data obtainable. References to articles on this and allied subjects are given in the bibliography at the end of the paper.

Energy consumption data used in this study are for the system as a whole and represent the total energy purchased and generated by the company. The purchased energy was metered at the substation a-c bus bars before transformation, conversion, and distribution, so that these losses were included.

The generated energy was metered at the generator bus bars before conversion and distribution. Hence, the energy data included not only the actual energy used in the propulsion of the cars, but also the d-c distribution losses and the losses in the converters and their transformers. Included in this total energy originally was all energy used for other purposes, such as that used in the general and divisional repair shops, car shed lighting, electric heaters, compressors and lighting on the cars, that sold to other public utilities, and that used for all other purposes. Energy balances were computed, and all of this consumption was segregated carefully, either by metering where possible or by estimates, and was deducted from the gross figures; thus the net energy consumption of the street cars was obtained at the substation or generator bus bars.

This total consumption then was divided by the total car miles operated on the system, which data are kept by the statistical department of the company. Thus was obtained an over-all energy consumption in kilowatthours per car mile. No adjustment was, or could be, made for the different classes of equipment. The types of cars, however, remained practically the same throughout the years used in these studies. The consumption per car mile was calculated by months for 5 years. This entire study has been spread over a period of almost 10 years. Many curves were drawn and many trials made before the results presented were considered to be reliable.

Of the 6 factors causing variation in energy consumption as mentioned in the first part of this paper, certain years could be selected wherein some of these factors were nearly constant. For the 5 years between 1916 and 1921, the scheduled speed of operation was practically constant; the vehicular traffic was increasing somewhat, but not nearly at as fast a rate as in later years; the mechanical equipment, because of the regular routine of inspection and overhaul, was in approximately the same operating condition; and no effort during those years was made to increase the efficiency of the motormen. This left only 2 variables: weather conditions, and passengers carried.

With 2 unknown variables and 1 known factor, the equation was difficult to solve mathematically. It was done, however, by a "cut and try" method. First, the relationship between the energy consumption and the weather was established; then using the corrections thus obtained, the effect of the weather was eliminated, and the relationship between the energy and the passengers was determined. Both of these figures were in error; the first because the effect of the passengers was not eliminated, and the second because the factor for weather variation still was affected by the passengers. So another trial was made. Taking the relation between energy and passengers as originally established, the original energy figures were corrected for this variation after which the effect of the weather again was determined. This second curve took a logical shape, entirely different from the first as published in a previous article.[5] Again correcting the energy figures for weather variation, the effect of passengers was determined for a second time, and this curve also was much more logical. This whole process was repeated a third time, and by this successive elimination of each of the 2 variables, the final results are believed to be accurate.

5. For numbered references, see bibliography at end of paper.

Weather Conditions

In the beginning of the study it was noticed that the energy consumption per car mile was lowest in July, the month having the highest average temperature, and highest in the coldest months. The energy consumption for July therefore was taken as unity and the consumption for all other months in the same year was divided by that figure. This quotient was called the "temperature correction factor" and was expressed decimally. It has been plotted against the average monthly temperature, and is shown in Fig. 1. By means of this curve, the temperature correction factor may be found for any month corresponding to the average monthly temperature, and the energy consumption then may be reduced to a uniform basis, thus eliminating the effect of climatic changes.

The mean monthly temperature is used instead of rainfall, snow, or other variables, because it is the best and most available measure of the weather. The temperature of any month reflects the weather conditions, and the data clearly show the variation of the energy consumption with the mean temperature, whereas no relationship has been found for other conditions.

Figure 1 shows that as the temperature decreases the energy consumption increases, slowly in the warmer months and quite rapidly during the winter season. The curve becomes asymptotic at about 75 deg F, the usual mean temperature for the month of July. When the mean temperature falls to the freezing point, the energy consumption increases approximately 10 per cent over that in July, other factors remaining constant. This increase in energy results from: greater friction losses in bearings; unfavorable rail conditions due to the rains, snow, sleet, and frost that usually accompany the lower temperatures in this climate; higher winds, both

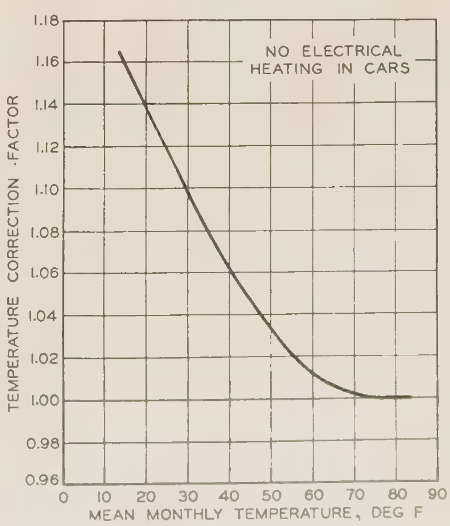

Fig. 1. Relation between energy consumption and weather conditions

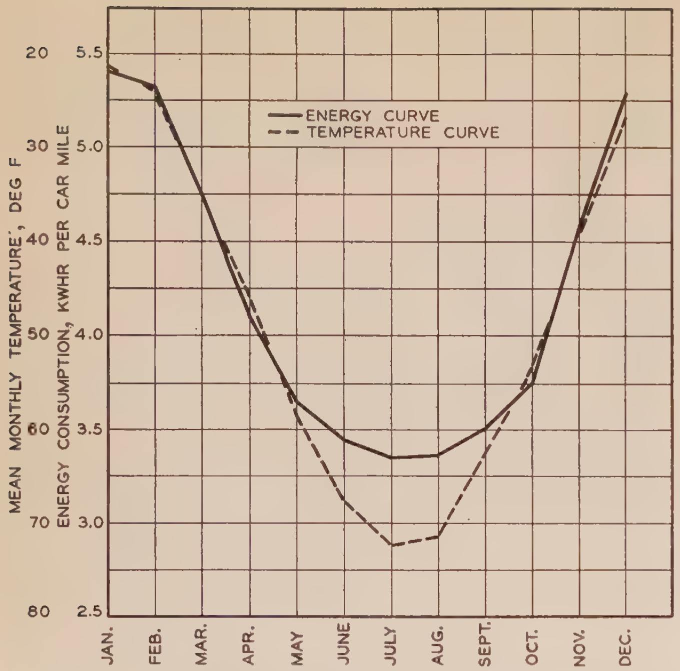

Fig. 2. Monthly comparison of energy consumption and mean temperature for a street railway in the northeastern United States

head winds and side winds, which cause greater head-on and side pressures; slower operation due to the bad conditions which causes lost time and inefficient operation in an effort to make up this time; slower movements of both passengers and crews due to the cold and to the heavier clothing worn; denser and more slowly moving vehicular traffic caused by the bad weather, and so forth. All of these items have an effect in varying degrees.

In this study, the energy used in electric heaters was subtracted from the totals, as only a few cars were equipped with this type of heater. In the colder climates and where all of the car heating is done by electricity, the effect of the heating plus the effect of the weather conditions so far overbalances the other variables that they may be neglected. This is shown very plainly in Fig. 2, the data for which were obtained on a street railway in the northeastern part of the country and represent averages for 5 years. Except for the 3 summer months of June, July, and August, the inverted curve of monthly temperature and the energy consumption curve are almost identical. A temperature correction curve also was drawn for this railway (see Fig. 3). This curve has the same shape as the one in Fig. 1, but the factors are much greater, the energy being 50 per cent greater in the months having a mean temperature of 32 deg than in midsummer.

Passengers

After the temperature correction factor was determined, it was a relatively easy matter to reduce all of the energy consumption figures per car mile to the same basis, by dividing each figure by this factor. With the effect of variations in the weather compensated, and with the schedule speed of the cars remaining approximately the same, the passengers per car mile were plotted against the energy consumption; the result is shown in Fig. 4. This curve has been checked against relationships obtained for other street railways, and in general is applicable although local conditions may affect the slope of the curve somewhat. The relationship between these 2 variables changes with the slope of the curve; the steeper the curve, the less effect the passenger load has on the energy consumption. The curve in Fig. 4 shows that for each 1-per cent increase in passengers carried the energy consumption increases 0.75 per cent. On other railways this increase in energy has been from 0.56 to 0.80 per cent.

The greatest element in the effect of an increase in the passengers carried is the number of car stops required per mile. In general, the more the passengers, the greater the number of stops, and the

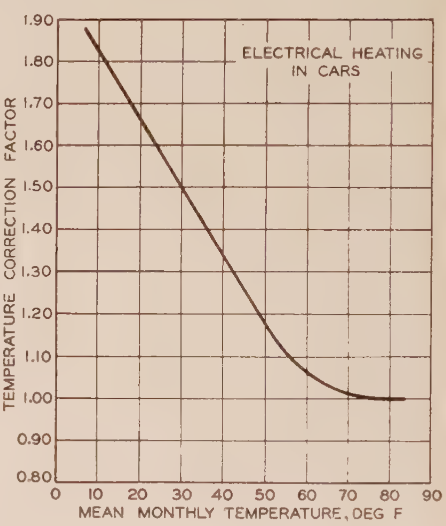

Fig. 3. Relation between energy consumption (including electrical heating) and weather conditions

greater the energy consumption. This has been shown repeatedly in previous papers and articles.[1,10]. The reason is clear. For any given line, or system, the schedule speed has been set for average operation which anticipates a certain number of stops per mile, or per route, and a definite time has been set in which the motorman must make his run. As the loads increase beyond the average, greater time is required to load and to discharge passengers at each stop, and more stops are required. Each second that the motorman loses at a stop means that that much more time must be made up to prevent his falling behind schedule; and as he loses time, or, rather, as he endeavors to make up lost time, he increases the energy consumption of his car by driving it faster and coasting less. Any one who has operated a car knows this fact even without it having to be proved by the use of meters. The weight of the additional passengers has an effect, but this effect is small compared with the foregoing reason, even though the energy varies directly with the total weight. For example, assume a car weighing 42,500 lb net, and a passenger load of 50 at an average weight of 150 lb each. The total load is then 50,000 lb. If the passenger loading be doubled, the total weight of the car increases to 57,500 lb, an increase of only 15

per cent, whereas the actual energy consumption increases much more.

No claim is made that the curve in Fig. 4 represents the variation in passenger loading throughout the entire range on any one car. This relationship holds only for a system load, within the range usually encountered in month by month, or year by year, variations. An entirely different problem is presented, and new curves would have to be drawn from data not now available, in order to obtain the relationship with the energy consumption over the whole range from zero loading to a crowded car.

Speed

The term "speed" as used in this paper refers to the average monthly speed of the entire system. It is calculated by dividing the total car miles operated during any month by the total platform hours worked. It is not therefore the speed of any particular car, but is the average speed for the system. Included in the time are all stops, lay-overs, and delays occurring during normal or abnormal operation.

In the years during which the other data were developed, this scheduled speed was practically constant, varying less than 0.5 per cent from the average. In later years, efforts were made to speed up schedules, and to reduce the running time so as to reduce platform hours and to give better service. This increase in speed was not obtained by changing the equipment nor by the purchase of new cars, but

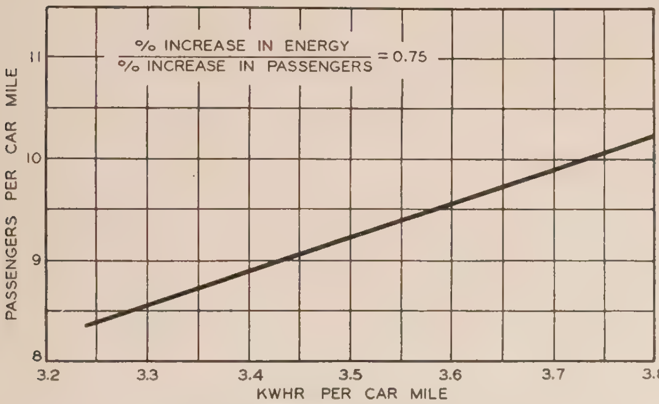

Fig. 4. Relation between energy consumption and passengers carried

by the elimination of waste time and by reducing the running time between time points. This latter caused faster acceleration and braking by making the motormen operate more rapidly. The total change in speed was a little more than 5 per cent, varying from 9.8 to 10.4 mph.

Figure 5 shows the relation between the change in speed and the change in energy consumption. Data for this curve were calculated in the same manner as for the previous ones. The actual energy consumption was divided by the temperature correction factor to reduce the energy to uniform weather conditions. Then the energy figures were adjusted to a uniform value for passengers per car mile, 9.24, which was the average loading for the first year. These adjusted energy figures then were plotted for each month against the average speed for the same month. It was determined in this manner that the energy consumption was increased 1.8 times the increase in speed. It must be borne in mind that this relationship is only for that part of the speed curve lying approximately between the limits of about 8 to 12 mph.

The curve of Fig. 5 was checked by drawing a speed time curve for one type of car on one particular line. Then taking that section of the speed time curve between 8 and 12 mph, the energy was calculated for this section and plotted against the speed. The result showed that the energy increase was double the speed increase. This was considered a good check, as no data from other systems were available.

Vehicular Traffic

No definite data could be obtained as to the relationship of energy to the density of street traffic. Without question traffic has some effect on the energy, because the car movements are retarded. Various methods were tried, but all failed because no apparent means of measuring the density of traffic seemed to be available. The vehicular registration shows only the increases by years, and are of no value here. An effort was made to determine the amount of gasoline consumed by months, but this could not be done. Although in St. Louis there is a gasoline tax, this is reported only by quarterly periods and frequently one period was heavily loaded with gasoline to be consumed in the next quarter, and *vice versa*. If the gasoline consumption could be determined accurately for any area, such as a city or metropolitan district, this would be a good measuring stick for the density of traffic.

However, it is not believed that the density of traffic has had nearly as great an effect upon energy consumption as has the weather, speed, or passengers, because, although traffic has increased tremendously

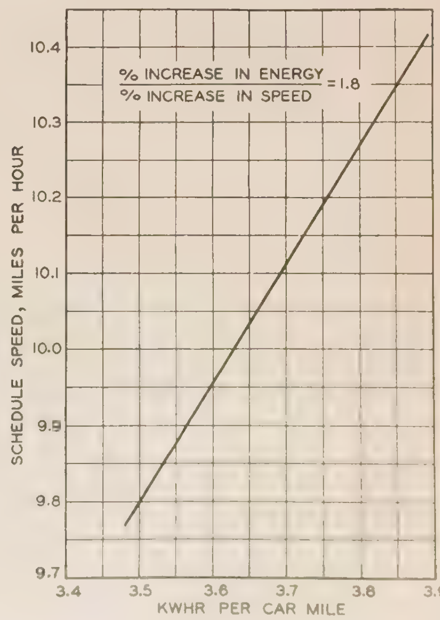

Fig. 5. Relation between energy consumption and schedule speed

in the past 10 years, the actual effect upon street car movements is limited to certain restricted areas which are small compared with the system as a whole. A second reason is that under normal conditions the traffic moves relatively rapidly and can clear the streets quickly. In bad weather, however, dense traffic or light traffic moves very slowly and has a habit of staying in the rails, probably with the idea that the rails will prevent skidding. At these times, the density has a very decided effect upon energy consumption, but a good part of this effect already is reflected in the factors for the weather conditions.

Condition of the Equipment

The physical condition of the equipment has a decided influence upon energy consumption. Cars with tight brakes or bearings use much more energy than necessary under better conditions. The energy consumption per mile will differ for cars of the same series, even though of the same weight and having the same equipment, all other conditions remaining the same. This is because the cars go through the shops periodically and are adjusted to take up wear, etc. Although efforts are made to adjust each car to a standard, it is a practical impossibility to adjust each car of any series so that all will be exactly alike. However, this variation of energy consumption is counterbalanced by the fact that a large number of cars of each series are averaged in all of the figures used, and as a result of the shop practice in use, the average condition of all cars will be approximately the same at all times.

Efficiency of the Motormen

By proper training and continued instruction, savings as great as 10 per cent or more in the total energy cost can be made. Operating men know this, and many articles published in the technical journals (see bibliography) bear out this assertion; but there is no measure by which to gauge the efficiency of a motorman, and consequently this efficiency cannot be plotted against the energy consumption. However, with the relationships that have been established in this study, it is quite possible to take the energy figures for a system and by reducing all of these figures to a common base, determine the effect of motorman instruction or of any other factor desired.

Power Demand

The figures and relationships that have been established have dealt entirely with the energy consumption. No mention has been made of power demand, or the effect of these variables upon the system peak load. Because of other studies, it is believed, but not proved, that the power demand will vary as will the energy, but that this variation will be somewhat smaller. That is, the weather, loading, and speed have less effect upon the power demand than upon the energy demand. Though it is possible to prove, it is rather difficult because of the complications that arise when it is desired to separate all of these figures for certain hourly periods of the day.

Discussion

As stated in the fore part of this paper, no claim is made for extreme accuracy of these figures. Too many variables are involved, and these variables are of such a nature that it is hard to evaluate them correctly. Care was used in the computation and plotting of the curves, but this, of course, does not change or improve the underlying inaccuracy of the basic figures.

The energy figures are metered and are the most accurate of all, probably within 0.5 per cent; but the necessary deductions made therefrom for energy used for purposes other than car propulsion are accurate only within 5 per cent. Data on the mean monthly temperature were obtained from the United States Weather Bureau, and should be accurate within less than 1 per cent. The number of passengers carried and the car miles operated depend upon reports turned in by the car crews, and are therefore more inaccurate than metered values, but are probably within 2 per cent of the true quantities. Hence, under the most unfavorable conditions with all of the errors additive, the maximum error should not exceed 8 per cent. It is believed that the relationships established are accurate within 5 to 8 per cent.

The data herein presented are of value to the street railway management, transportation officials, superintendents of power, the power companies, and all interested in the economics of street railways. By use of these relationships the effect of changing schedules to speed up the service, of handling more or less passengers, and of the weather conditions all can be predetermined, and the energy consumption anticipated. They also can be used for the purpose of determining the effect on energy consumption of any changed operating method desired.

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Decrement Curves for Power Systems

A set of decrement curves useful in determining the magnitude of short-circuit currents on power systems has been calculated, based upon assumptions somewhat different from those used for previous decrement curves. These changes are intended to increase the usefulness of such curves and extend their range of application. Proper selection of oil circuit breakers and the determination of relay setting may be facilitated by the use of these curves.

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In recent years many advancements have been made in the technique of analyzing short circuits on power systems. The method of symmetrical components has been developed by which the magnitude of the initial and sustained short-circuit currents is readily obtained. The problem of determining the short-circuit currents for a definite time between these 2 extremes has been solved for some years past by the use of decrement curves.[1, 2, 3] Recently, considerable progress has been made in determining the behavior of synchronous machines during short circuits, and decrement curves considering these new developments have been published by W. C. Hahn and C. F. Wagner.[1] The curves presented herewith have been constructed along lines similar to the curves referred to above, the changes being those of application rather than fundamental assumptions.

The curves of Hahn and Wagner were constructed using the following basic assumptions:

1. The generators were assumed to be operating at rated voltage, frequency, and kilovoltamperes at 0.80 lagging power factor immediately preceding short circuit.

2. The short circuit was assumed to occur at the point of the voltage wave which corresponds to the maximum possible instantaneous current.

3. All resistance in the circuit including the resistance of the fault was neglected.

4. The actual system subjected to fault could be represented by a single equivalent generator of the same total kilovoltampere rating and external reactance.

5. No automatic voltage regulators were used.

6. The load was assumed to be located at the generator terminals, and the generator reactance was taken as 15 per cent. In cases where the total reactance to fault was less than 15 per cent, all the reactance was assumed to be in the generator.

7. All the machine electromotive forces were assumed to be in phase.

8. The short circuit was assumed to occur on an unloaded feeder.

9. The machine reactances and time constants were taken as representative of modern machines.

The present curves are based upon the same assumptions as the Hahn and Wagner curves with the following exceptions:

1a. The curves giving the maximum current assume that the generators are operating at rated voltage, frequency, and kilovoltamperes at 0.80 lagging power factor immediately preceding the short circuit.

1b. The curves giving the minimum current assume that the generators are operating at rated voltage, frequency, and no load, immediately preceding the short circuit.

2a. The curves giving the maximum current assume that the short circuit occurs at the point of the voltage wave which corresponds to the maximum possible current.

2b. The curves giving the minimum current assume that the short circuit occurs at the point of the voltage wave which corresponds to the minimum possible current.

3. The effect of resistance is considered in calculating the magnitude and rate of decay of the fault current. The impedance of the circuit external to the generator and load is assumed to have a ratio of resistance to reactance approximately equal to $^1/_8$. The impedance of the fault is assumed zero.

The following improvements should be noted. The extent of the curves and tables has been increased from the usual 100-per cent reactance to fault to 300-per cent reactance to fault. This makes possible the determination of currents for the 3 common types of faults (3 phase, line to line, and line to ground) up to a distance equal to approximately 100-per cent reactance from the generator. This is an increase in usefulness which should prove valuable from a practical standpoint. Resistance as well as reactance has been considered in computing both the initial currents and rates of current decay. Four decrement curves, and tables, are provided. The curves of Figs. 1 and 3 permit the determination of the maximum possible current corresponding to machines operating at normal full load excitation supplying a loaded system. The curves of Figs. 2 and 4 permit the determination of the minimum possible symmetrical current, corresponding to machines operating at no-load excitation. The 2 conditions determine the range of values to be expected, and permit an estimate of the probable currents for intermediate cases. One set, Figs. 1 and 2, is plotted in the conventional manner, and shows the effect of current decrement directly. The other, Figs. 3 and 4, has been arranged to expedite results obtained from calculating-table studies. For a complete discussion of terms used in this paper see reference 9.

Application of Decrement Curves

Under short-circuit conditions synchronous motors and condensers supply current to the fault during the transient period, and therefore all synchronous ma-

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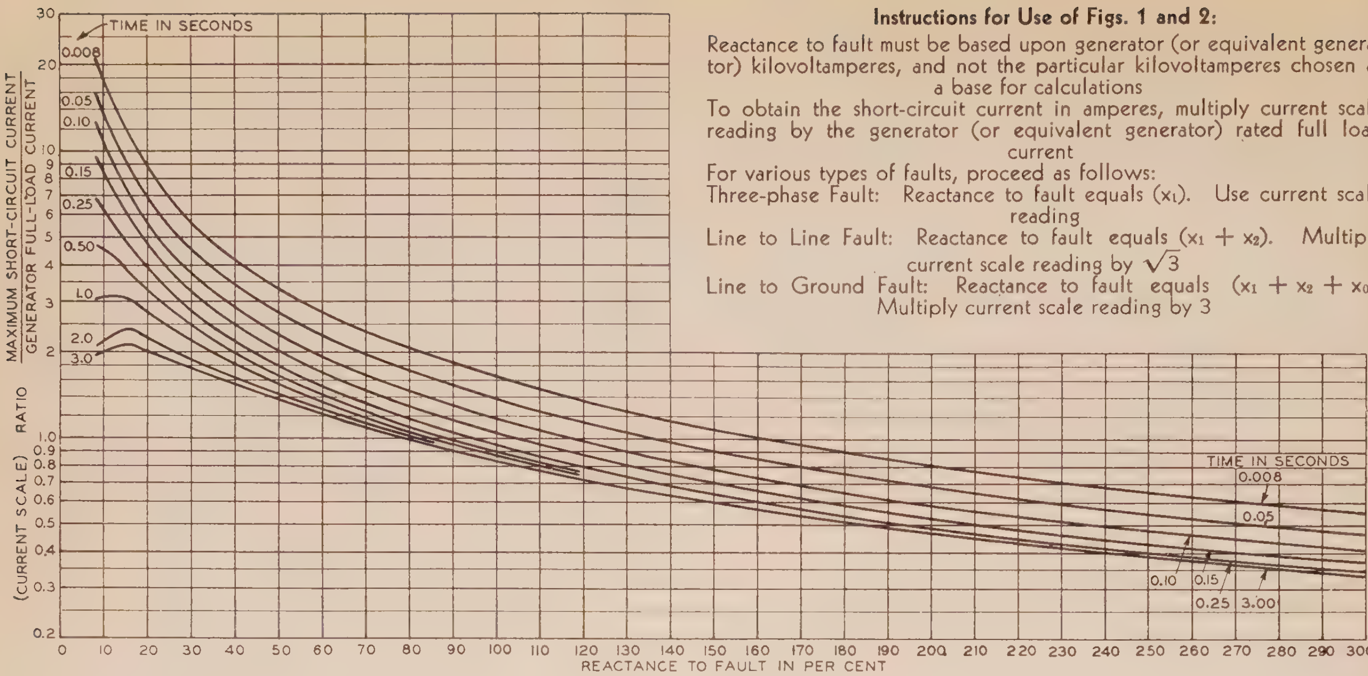
1. For all numbered references see list at end of paper.



Instructions for Use of Figs. 1 and 2:

Reactance to fault must be based upon generator (or equivalent generator) kilovoltamperes, and not the particular kilovoltamperes chosen as a base for calculations

To obtain the short-circuit current in amperes, multiply current scale reading by the generator (or equivalent generator) rated full load current

For various types of faults, proceed as follows:

Three-phase Fault: Reactance to fault equals (x_1). Use current scale reading

Line to Line Fault: Reactance to fault equals ($x_1 + x_2$). Multiply current scale reading by $\sqrt{3}$

Line to Ground Fault: Reactance to fault equals ($x_1 + x_2 + x_0$). Multiply current scale reading by 3

Fig. 1. Short-circuit decrement curves for power systems

Curves give root-mean-square maximum short-circuit current for various times after fault

Generators assumed operating at rated voltage, full load, 0.80 power factor, and without voltage regulators, immediately preceding short circuit

Curves are based on T_{do}' equal to 5 sec. For other values of T_{do}', multiply desired times by $5/T_{do}'$ to get proper time to use on curves

chines on a system are treated as generators during the initial period of a short circuit. It is important that the machines be represented by their subtransient reactances. The actual system must be reduced to as simple a system as possible. The decrement curves are derived for a system consisting of a single generator supplying a load at its terminals. The generator referred to in the paragraphs immediately following is assumed to be the equivalent generator resulting from the reduction process.

The curves of Figs. 1 and 2 give the maximum and minimum probable short-circuit currents, respectively, expressed in terms of the ratio of the actual short-circuit current to the equivalent generator full load current, for various per cent reactances to fault. The fault current in amperes is obtained by multiplying this ratio by the normal generator current in amperes. These curves are used in a manner similar to others which have been published from time to time.

The curves of Figs. 3 and 4 are constructed to give, respectively, the maximum and minimum short-circuit currents, the current being plotted in terms of the ratio of the actual short-circuit current to the instantaneous symmetrical short-circuit value. The fault current in amperes is obtained by multiplying this ratio by the instantaneous symmetrical short-circuit current in amperes. Since it is common practice to determine the instantaneous symmetrical short-circuit current as the first step in the solution of a problem, the use of these curves facilitates solution.

In most cases it will be sufficiently accurate to assume the open circuit time constant of the equivalent generator equal to 5 sec, which is the value used

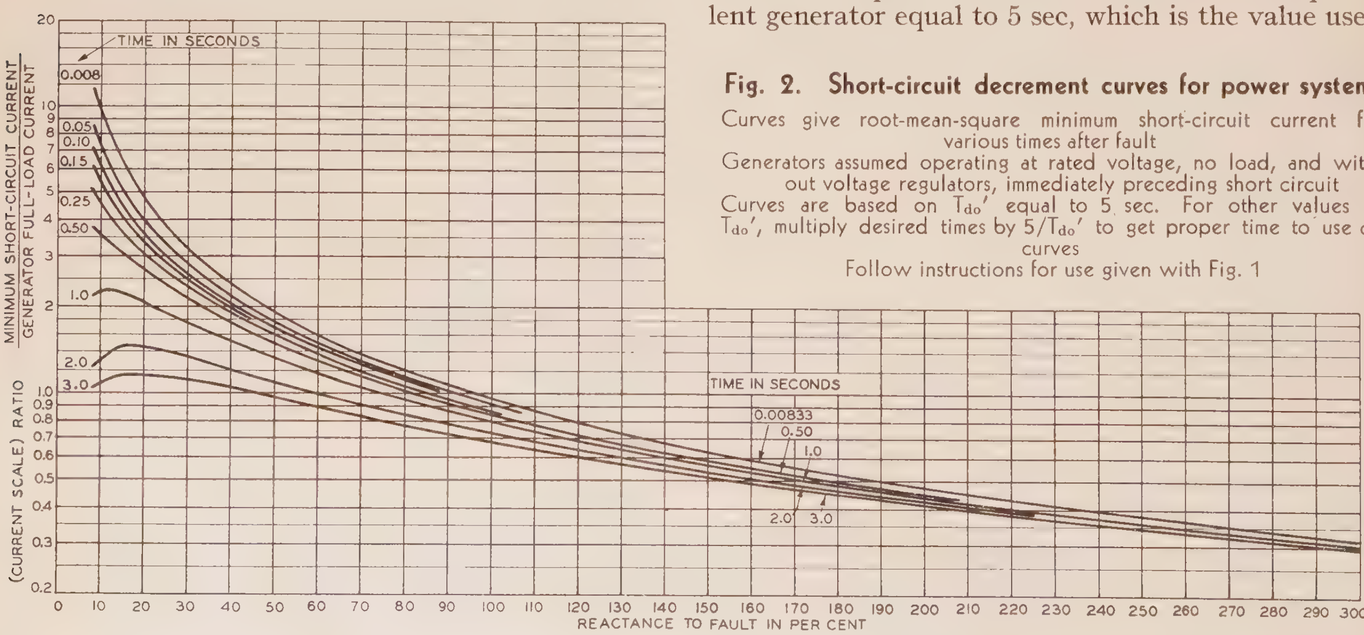


Fig. 2. Short-circuit decrement curves for power systems

Curves give root-mean-square minimum short-circuit current for various times after fault

Generators assumed operating at rated voltage, no load, and without voltage regulators, immediately preceding short circuit

Curves are based on T_{do}' equal to 5 sec. For other values of T_{do}', multiply desired times by $5/T_{do}'$ to get proper time to use on curves

Follow instructions for use given with Fig. 1

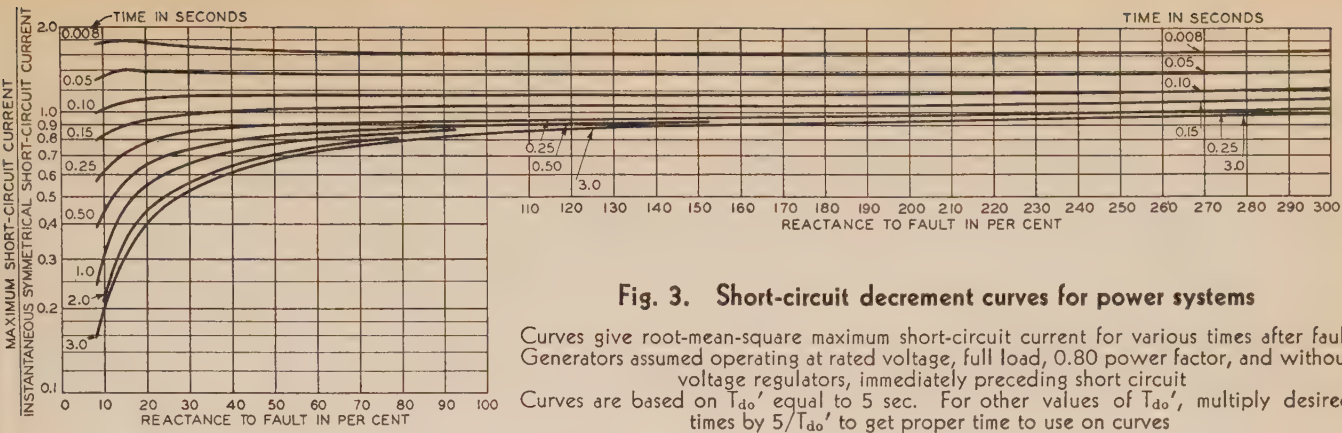


Fig. 3. Short-circuit decrement curves for power systems

Curves give root-mean-square maximum short-circuit current for various times after fault Generators assumed operating at rated voltage, full load, 0.80 power factor, and without voltage regulators, immediately preceding short circuit

Curves are based on T_{do}' equal to 5 sec. For other values of T_{do}', multiply desired times by $5/T_{do}'$ to get proper time to use on curves

Instructions for Use of Figs. 3 and 4:

Reactance to fault must be based on generator (or equivalent generator) kilovoltamperes, and not the particular kilovoltamperes chosen as a base for calculations

To obtain the short-circuit current in amperes, multiply current scale reading by instantaneous symmetrical short-circuit current, for type of fault considered

For various types of faults, proceed as follows:
Three-phase Fault: Reactance to fault equals (x_1)
Line to Line Fault: Reactance to fault equals $(x_1 + x_2)$
Line to Ground Fault: Reactance to fault equals $(x_1 + x_2 + x_0)$

n constructing the curves. If more accurate results re desired, the open circuit time constant can be alculated from the formula given below:[4]

$$_{doe}' = \frac{1}{x - x'} \sum (T_{do_1}(x_{d_1} - x_{d_1}')u_1^2 \ldots\ldots\ldots\ldots) \qquad (1)$$

r

$$_{doe}' = \frac{x^2}{x - x'} \sum (T_{do_1} \frac{(x_{d_1} - x_{d_1}')}{x_{d_{1f}}^2} \ldots\ldots\ldots\ldots) \qquad (2)$$

here:

$_{doe}'$ = equivalent open circuit time constant
= synchronous reactance of system to fault
$'$ = transient reactance of system to fault
$_{do_1}$ = open circuit time constant of first machine
$_{d_1}$ = synchronous reactance of first machine
$_{d_1}'$ = transient reactance of first machine
$_{d_{1f}}$ = synchronous reactance of first machine to fault
$_1$ = ratio of sustained current in first machine to total sustained urrent in fault (all reactances must be expressed on the same kilo-oltampere base)

n cases where there is no appreciable reactance be-ween the machines and the point where the equiva-ent generator is assumed, this constant can be deter-nined roughly by simple proportion:

$$_{doe}' = \sum (T_{do_1} \frac{kva_1}{kva_t} \ldots\ldots\ldots\ldots) \qquad (3)$$

here:

va_1 = kva capacity of first machine
$_{do_1}$ = open circuit time constant of first machine, etc.
va_t = total kilovoltampere capacity of system.

The instructions given on the curves are sufficient for ordinary use. If the open circuit time constant is other than 5 sec, an approximate correction should be made. The desired time is multiplied by 5 divided by the actual time constant. The result can then be used in determining values from the curves. Curves showing typical open circuit time constants of synchronous machines are given in Figs. 5 and 6, which have been taken from Hahn and Wagner.

The reactance to fault must be referred to the equivalent generator capacity in kilovoltamperes as a percentage, and not to the arbitrary kilovoltampere base used for calculations. The resistance of the actual system must be neglected in this determination, proper account having been taken of the average system in deriving the curves.

Three-Phase Short Circuits. The reactance to fault is the positive sequence reactance (x_1), the value which ordinarily determines the instantaneous symmetrical short-circuit current for this type of fault. The reactance to fault is the generator subtransient reactance plus the external reactance to fault $(x_1 = x_d'' + x_b)$. The current scale gives the current as described previously.

Line to Line Short Circuits. The reactance to fault

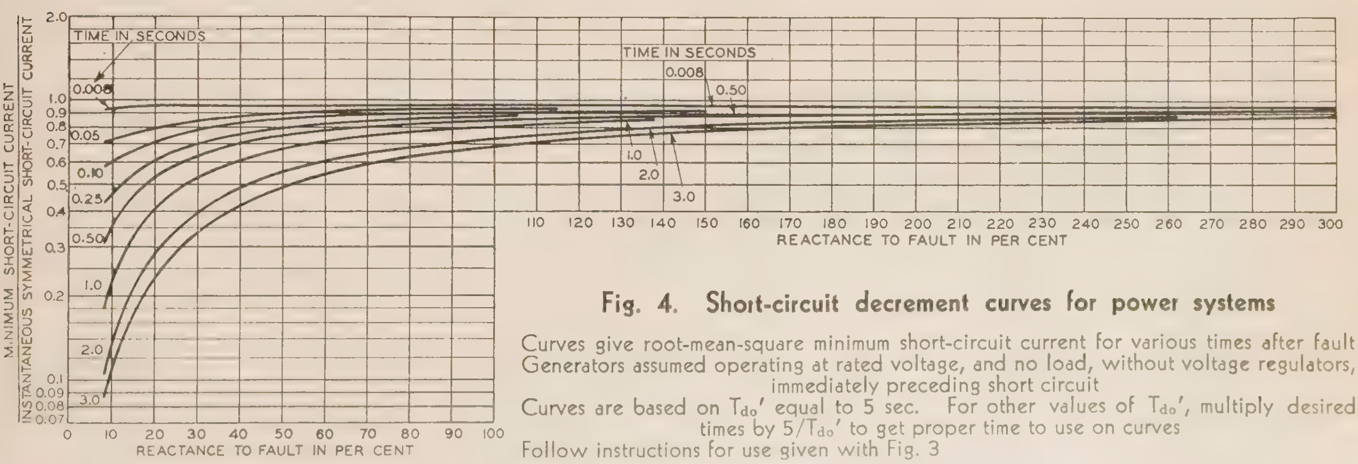


Fig. 4. Short-circuit decrement curves for power systems

Curves give root-mean-square minimum short-circuit current for various times after fault Generators assumed operating at rated voltage, and no load, without voltage regulators, immediately preceding short circuit

Curves are based on T_{do}' equal to 5 sec. For other values of T_{do}', multiply desired times by $5/T_{do}'$ to get proper time to use on curves

Follow instructions for use given with Fig. 3

is the sum of the positive sequence reactance plus the negative sequence reactance to fault $(x_1 + x_2)$. Since the values of generator subtransient reactance and negative sequence reactances are nearly equal numerically, it is generally sufficiently accurate to use twice the positive sequence reactance to fault $(2x_1)$.

The current in amperes is obtained from Figs. 1 and 2, by multiplying the current scale reading by the generator normal full load current and by $\sqrt{3}$. No such calculation is required when using the curves of Figs. 3 and 4.

Line to Ground Short Circuits. The reactance to fault is the sum of the positive, negative, and zero sequence reactances to fault $(x_1 + x_2 + x_0)$. As before, this reactance may be taken equal to twice the positive plus the zero sequence reactance $(2x_1 + x_0)$. The corrections for open circuit time constant apply as before. The current in amperes is obtained from Figs. 1 and 2, by multiplying the current scale reading by the generator full load current and by 3. No such calculation is required when using the curves[5] of Figs. 3 and 4.

Except as noted, both sets of curves are used in the same manner, and give identical results for any given case. The values used in constructing the curves are given in Tables I to V, inclusive. It is obvious that the required results can be obtained from either the proper curve or table.[6]

The curves are constructed assuming that no automatic voltage regulators are used. Where the actual machines are equipped with voltage regulators, they will tend to compensate for the effects of current decrement. However, if a regulator is furnished with an overcurrent protective relay, the latter will disconnect the regulator before it has had time to operate, and the curves may be used. In case the regulator is not provided with a protective relay, and quick response system is not used, the curves may be used up to the first 1/4 sec after fault, since the regulator requires some time to operate. Regardless of the type of excitation system, the curves may be used to determine the initial currents, and

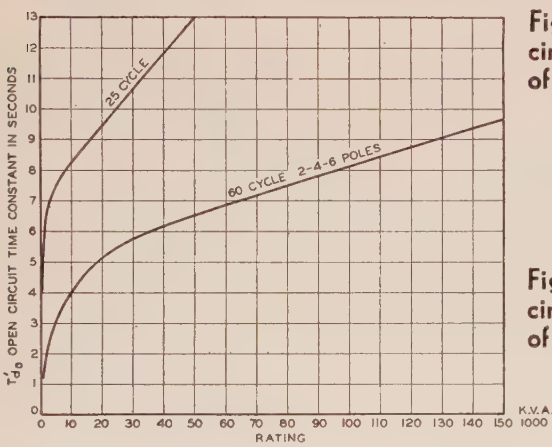


Fig. 5 (left). Open circuit time constants of turbine-generators

Fig. 6 (right). Open circuit time constants of a-c generators and motors

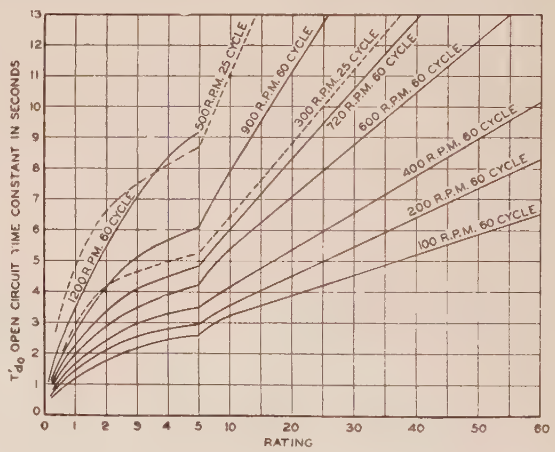


Table I—Decrement Curve Construction

Assumed Generator Constants:

$x_d = 1.15$ $\quad x_d' = 1.4x_d'' + 0.02$ $\quad\quad x_1 = x_d'' + x_b$

$x_q = 1.00$ $\quad x_d'' = x_1$, for x_1 less than 0.15

$T_{do}' = 5.00$ $\quad x_d'' = 0.15$, for x_1 greater than 0.15

Assumed System Constants:

$Z_b = z_b \angle 72.0° = 0.325x_b + jx_b$ $\quad\quad Z_f = z_f \angle 36.8° = 0.8 + j0.6$

x_1	0.08	0.10	0.12	0.15	0.20	0.30	0.40	0.50	0.75	1.00	1.50	2.00	2.50	3.00
x_d''	0.08	0.10	0.12	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
x_d'	0.132	0.160	0.188	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
I''	12.5	10.0	8.33	6.66	5.00	3.33	2.50	2.00	1.33	1.00	0.67	0.50	0 40	0.33
Maximum Current Curve Construction														
e_d''	1.05	1.06	1.08	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
e_d'	1.08	1.10	1.12	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
e_d	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92
e_{da}	2.17	2.19	2.22	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
i''	13.1	10.6	8.96	7.32	5.32	3.43	2.52	1.99	1.31	0.975	0.645	0.483	0.388	0.330
i'	8.20	6.91	5.98	5.00	3.98	2.81	2.18	1.76	1.21	0.915	0.619	0.468	0.388	0.330
i	1.89	1.91	1.93	1.99	1.83	1.58	1.39	1.25	0.975	0.802	0.592	0.468	0.388	0.330
R					0.017	0.038	0.091	0.127	0.21	0.28	0.38	0.45	0.506	0.55
X					0.047	0.129	0.194	0.249	0.345	0.407	0.478	0.517	0.541	0.553
T_d'	0.574	0.695	0.818	1.00	1.16	1.41	1.59	1.74	1.99	2.15	2.33	2.44	2.52	2.58
Minimum Current Curve Construction														
e_{da}	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
i''	12.5	10.0	8.33	6.66	5.00	3.30	2.45	1.95	1.29	0.965	0.641	0.479	0.382	0.318
i'	7.58	6.25	5.32	4.34	3.57	2.61	2.06	1.70	1.17	0.90	0.61	0.461	0.372	0.311
i	1.00	1.00	1.00	1.00	0.959	0.885	0.821	0.766	0.654	0.566	0.455	0.376	0.321	0.280
R					0.016	0.049	0.081	0.114	0.195	0.276	0.438	0.602	0.765	0.925
X					0.050	0.15	0.25	0.35	0.60	0.85	1.35	1.85	2.35	2.85
T_d'	0.574	0.695	0.818	1.00	1.17	1.46	1.73	1.95	2.41	2.75	3.22	3.53	3.75	3.91

Table II—System Short-Circuit Current Decrement Factors, Minimum Probable Current

Rms Total Current Expressed as a Ratio Equal to: $\dfrac{\text{Minimum Short-Circuit Current}}{\text{Generator Full Load Current}}$ for Various Reactances to Fault (in Per Cent x_1)

Time in Sec	8	10	12	15	20	30	40	50	75	100	150	200	250	300
0.008	11.6	9.35	7.83	6.30	4.78	3.19	2.39	1.91	1.27	0.96	0.636	0.476	0.381	0.317
0.05	8.84	7.25	6.17	5.03	3.99	2.81	2.18	1.77	1.21	0.92	0.619	0.466	0.375	0.313
0.10	7.19	6.06	5.26	4.34	3.54	2.59	2.04	1.69	1.17	0.90	0.610	0.460	0.371	0.311
0.15	6.30	5.42	4.72	3.98	3.33	2.47	1.97	1.64	1.15	0.88	0.603	0.457	0.370	0.310
0.25	5.29	4.58	4.20	3.61	3.08	2.33	1.89	1.59	1.12	0.87	0.598	0.455	0.369	0.309
0.50	3.75	3.56	3.34	3.03	2.66	2.11	1.75	1.49	1.08	0.84	0.588	0.450	0.367	0.308
1.00	2.16	2.25	2.27	2.23	2.07	1.75	1.51	1.32	1.00	0.80	0.568	0.440	0.360	0.304
2.00	1.20	1.29	1.37	1.45	1.42	1.33	1.21	1.09	0.88	0.73	0.538	0.424	0.351	0.299
3.00	1.03	1.07	1.11	1.16	1.15	1.11	1.04	0.97	0.803	0.68	0.516	0.412	0.344	0.294

Time in seconds is the time from instant of short circuit

Table III—System Short-Circuit Current Decrement Factors, Minimum Probable Current

Rms Total Current Expressed as a Ratio Equal to: $\dfrac{\text{Minimum Short-Circuit Current}}{\text{Instantaneous Symmetrical Short-Circuit Current}}$ for Various Reactances to Fault (in Per Cent x_1)

Time in Sec	8	10	12	15	20	30	40	50	75	100	150	200	250	300
0.008	0.932	0.935	0.940	0.945	0.955	0.957	0.955	0.956	0.953	0.960	0.954	0.952	0.953	0.952
0.05	0.706	0.725	0.741	0.755	0.798	0.843	0.871	0.885	0.905	0.920	0.929	0.932	0.936	0.940
0.10	0.575	0.606	0.631	0.655	0.708	0.776	0.815	0.845	0.877	0.900	0.915	0.920	0.927	0.933
0.15	0.504	0.542	0.565	0.597	0.666	0.741	0.788	0.820	0.862	0.880	0.905	0.915	0.925	0.930
0.25	0.424	0.458	0.504	0.542	0.616	0.699	0.756	0.795	0.840	0.870	0.897	0.910	0.923	0.926
0.50	0.300	0.356	0.402	0.455	0.532	0.632	0.700	0.745	0.810	0.840	0.882	0.900	0.915	0.924
1.00	0.173	0.224	0.273	0.334	0.414	0.525	0.604	0.660	0.748	0.800	0.853	0.880	0.900	0.912
2.00	0.097	0.129	0.165	0.217	0.284	0.399	0.484	0.545	0.660	0.730	0.807	0.849	0.878	0.898
3.00	0.083	0.107	0.134	0.174	0.230	0.333	0.416	0.484	0.602	0.680	0.774	0.822	0.860	0.882

Time in seconds is the time from instant of short circuit

Table IV—System Short-Circuit Current Decrement Factors, Maximum Probable Current

Rms Total Current Expressed as a Ratio Equal to: $\dfrac{\text{Maximum Short-Circuit Current}}{\text{Generator Full Load Current}}$ for Various Reactances to Fault (in Per Cent x_1)

Time in Sec	8	10	12	15	20	30	40	50	75	100	150	200	250	300
0.008	21.5	17.4	14.7	12.0	8.81	5.68	4.18	3.30	2.18	1.62	1.07	0.807	0.650	0.551
0.05	16.1	13.3	11.4	9.35	6.94	4.59	3.42	2.72	1.82	1.36	0.905	0.684	0.553	0.464
0.10	12.3	10.2	8.82	7.31	5.57	3.75	2.85	2.28	1.54	1.16	0.778	0.584	0.479	0.407
0.15	9.75	8.25	7.31	6.03	4.67	3.25	2.49	2.01	1.38	1.04	0.705	0.531	0.436	0.372
0.25	6.95	6.06	5.48	4.76	3.84	2.78	2.17	1.78	1.23	0.940	0.637	0.486	0.402	0.342
0.50	4.66	4.40	4.15	3.84	3.24	2.44	1.96	1.63	1.16	0.891	0.614	0.468	0.388	0.330
1.00	3.00	3.10	3.13	3.10	2.74	2.19	1.81	1.54	1.12	0.873	0.610	0.468	0.388	0.330
2.00	2.08	2.19	2.28	2.40	2.21	1.88	1.62	1.41	1.06	0.846	0.604	0.468	0.388	0.330
3.00	1.92	1.98	2.03	2.14	1.99	1.75	1.51	1.34	1.03	0.830	0.599	0.468	0.388	0.330

Time in seconds is the time from instant of short circuit

Table V—System Short-Circuit Current Decrement Factors, Maximum Probable Current

Rms Total Current Expressed as a Ratio Equal to: $\dfrac{\text{Maximum Short-Circuit Current}}{\text{Instantaneous Symmetrical Short-Circuit Current}}$ for Various Reactances to Fault (in Per Cent x_1)

Time in Sec	8	10	12	15	20	30	40	50	75	100	150	200	250	300
0.008	1.72	1.74	1.77	1.80	1.76	1.71	1.67	1.65	1.64	1.62	1.61	1.61	1.63	1.65
0.05	1.29	1.33	1.37	1.40	1.39	1.38	1.37	1.36	1.36	1.36	1.36	1.36	1.38	1.39
0.10	0.983	1.02	1.06	1.10	1.12	1.13	1.14	1.14	1.15	1.16	1.17	1.17	1.20	1.22
0.05	0.781	0.825	0.876	0.905	0.936	0.974	0.995	1.01	1.03	1.04	1.06	1.06	1.09	1.12
0.25	0.556	0.606	0.657	0.714	0.768	0.835	0.869	0.885	0.922	0.940	0.955	0.970	1.01	1.02
0.50	0.374	0.440	0.497	0.576	0.648	0.732	0.784	0.815	0.870	0.891	0.920	0.936	0.970	0.991
1.00	0.240	0.310	0.376	0.465	0.548	0.656	0.724	0.770	0.836	0.873	0.915	0.936	0.970	0.991
2.00	0.167	0 219	0.264	0.360	0.441	0.564	0.648	0.705	0.796	0.846	0 905	0.936	0.970	0.991
3.00	0.154	0.198	0.243	0.321	0.398	0.526	0.604	0.670	0.772	0.830	0.900	0.936	0.970	0.991

Time in seconds is the time from instant of short circuit

ie sustained currents can be estimated by multilying the calculated sustained current by the ratio the maximum exciter current to the nominal exter current. The nominal exciter current is that value of excitation required to produce rated voltage at the machine terminals before fault. In any case, it should be safe to assume that the maximum current will not exceed either the initial current or the

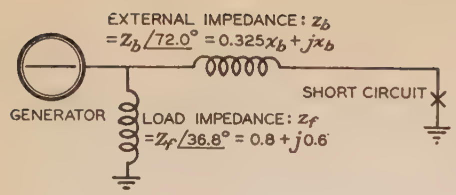
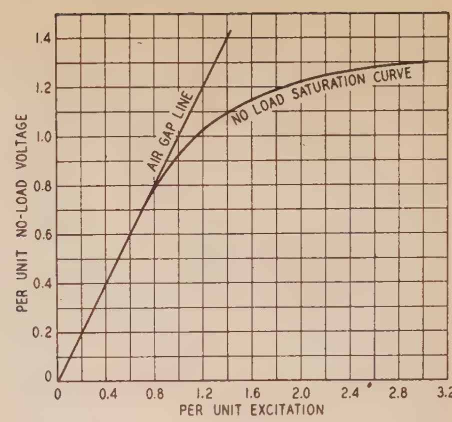


Fig. 7. Diagram of typical system

Fig. 8. Typical saturation curve



sustained current. Values of sustained currents i are given in Table I.

Conclusions

It is important to note that the results obtained using decrement curves on an actual system are at best approximate due to the assumptions used, and in cases demanding accurate results, rigorous methods must be used. For instance, the assumption that the arc resistance is zero is rarely met in practice. The assumption that the generated voltages are in phase assumes that the machines slow down together, again a condition rarely observed in practice. The present curves and tables are subject to the limitations discussed by Hahn and Wagner, and the reader is referred to their article for comprehensive treatment. Special attention is called to their discussion regarding salient pole machines without dampers.

A ready means of estimating fault currents on actual systems is of value, and it is believed that the results obtained using these decrement curves and tables will be sufficiently accurate to permit proper selection of oil circuit breakers and relay settings on the ordinary power system.

Appendix I—Derivation of Decrement Curves

In previously published decrement curves it has been assumed that all reactance was in the generator for values of x_1 less than 0.15. For values of x_1 greater than 0.15, this value was assumed in the generator and the remainder external thereto. As this assumption has been generally accepted, it is used in the present curves. The generator transient reactance x_d' is taken equal to $1.4x_d'' + 0.02$, and the Potier reactance x_p to $1.3x_d''$. The generator synchronous reactance in the direct axis x_d is assumed to be 1.15, and the quadrature axis synchronous reactance x_q to be 1.00.

The relation between the direct-axis transient short-circuit time constant T_d', and the direct-axis open-circuit time-constant T_{do}', for machines without saturation, when short-circuited through an external resistance r is:[7,8]

$$T_d' = \frac{T_{do}'}{\left[1 + \frac{x_q(x_d - x_d')}{r^2 + x_d'x_q}\right]}$$

When the machine is short-circuited through an external impedance $(r + jx)$, the formula becomes:

$$T_d' = \frac{T_{do}'}{\left[1 + \frac{(x_q + x)(x_d - x_d')}{r^2 + (x_d' + x)(x_q + x)}\right]} \tag{4}$$

This equation is used to determine the short-circuit time constant, assuming that the effects of saturation are negligible. The open-circuit time constant is taken as 5 sec, which is an average value for modern machines.

The external impedance is assumed to have a ratio of resistance to reactance equal to 1/3.077 (corresponding to an impedance angle of 72 deg.).

The curves giving the maximum current are obtained as follows. The current supplied by the generator equals the internal voltage previous to fault divided by the impedance to fault. The current supplied to the fault is less than the generator current because some of the current is taken by the load (see Fig. 7). The internal voltages are computed using round rotor theory and neglecting saturation except in the calculation of the sustained currents.

The magnitude of the internal voltage behind the subtransient reactance e_d'' immediately before short circuit is:

$$e_d'' = \sqrt{(E_t + Ix_d'' \sin \phi)^2 + (Ix_d'' \cos \phi)^2}$$
$$= \sqrt{(1.00 + 0.6x_d'')^2 + 0.64\, x_d''^2}$$

in which E_t is the generator terminal voltage before fault (E_t = 1.00), I is the load current before fault (I = 1.00), and ϕ is the load power factor angle (ϕ = 36.8 deg). Similarly, the magnitude of the internal voltage behind the transient reactance e_d' immediately before short circuit is:

$$e_d' = \sqrt{(1.00 + 0.6\, x_d')^2 + 0.64x_d'^2}$$

and the magnitude of the internal voltage behind synchronous reactance e_d immediately before short circuit (neglecting saturation) is:

$$e_d = 1.92$$

The correction for saturation is computed corresponding to the actual voltage generated in the machine using the Potier reactance. The correction is obtained by measuring the difference between the air gap saturation line and the typical no-load saturation curve of Fig. 8, for the value of actual generated or virtual voltage e_v. The magnitude of the virtual voltage of the machine immediately before short circuit is:

$$e_v = \sqrt{(1.00 + 0.78x_d'')^2 + 1.08x_d''^2}$$

The actual internal voltage e_{da} equals the arithmetic sum of the internal voltage plus the correction for saturation.

From Fig. 7, it is evident that the magnitude of the initial subtransient current supplied to the fault is:

$$i'' = \frac{e_d''}{x_d'' + \frac{z_b z_f}{z_b + z_f}} \cdot \frac{z_f}{z_b + z_f}$$
$$= \frac{e_d''}{\sqrt{x_b^2(0.325 - 0.606\, x_d'')^2 + (x_b + x_d''\{1.00 + 0.86\, x_b\})^2}}$$

The magnitude of the initial transient current in the fault equals:

$$i' = \frac{e_d'}{\sqrt{x_b^2(0.325 - 0.606x_d')^2 + (x_b + x_d'\{1.00 + 0.86\, x_b\})^2}}$$

Similarly, the magnitude of the sustained current in the fault equals:

$$i = \frac{e_{da}}{\sqrt{0.138x_b^2 + (1.99x_b + 1.15)^2}}$$

The direct-axis transient short-circuit time constant equals (from eq 4):

$$T_d' = \frac{5.00}{\left[1 + \frac{(x_q + X)(x_d - x_d')}{R^2 + (x_q + X)(x_d' + X)}\right]}$$

where R and X are the equivalent resistance and reactance respectively, of the parallel circuit consisting of the load and external

impedance. Expressed in terms of the external reactance to fault they are:

$$R = \frac{x_b(0.8\,x_b + 0.294)}{x_b^2 + 1.56\,x_b + 0.906} \qquad X = \frac{x_b(0.6\,x_b + 0.906)}{x_b^2 + 1.56\,x_b + 0.906}$$

The subtransient component of fault current at any time t equals:

$$i_{st} = (i'' - i')\epsilon^{-t/T_d''} = (i'' - i')\epsilon^{-t/0.05}$$

The value of T_d'' equal to 0.05 sec is an average value corresponding to $T_{do}' = 5$ sec.

The transient component of fault current at any time t equals:

$$i_t = (i' - i)\epsilon^{-t/T_d'}$$

The total symmetrical fault current is:

$$I_{ac} = i + i_t + i_{st}$$

The direct component of fault current at any time t equals:

$$I_{dc} = \sqrt{2}\,i''\,\epsilon^{-t/T_a} \text{ is } = \sqrt{2}\,i''\epsilon^{-t/0.15}$$

where T_a, the short-circuit time constant of the circuit is given an average value of 0.15 sec.

The magnitude of the total short-circuit current in the fault is:

$$I_{sc} = \sqrt{I_{ac}^2 + I_{dc}^2}$$

Values of current computed as outlined above are included in Table I, IV, and V, and give the current from the first quarter cycle to 3 sec after fault. The values have been plotted to give the curves of Fig. 1. The curves of Fig. 3 were obtained by plotting the ratio of the short-circuit current to the instantaneous symmetrical short-circuit current ($I'' = 1/(x_d'' + x_b)$).

The curves giving the minimum current are obtained in a similar manner. All internal voltages are unity for this case, since the machine is assumed to be operating at no load previous to fault. The correction for saturation is taken equal to 0.15, and the load is omitted. Since the absolute minimum current is desired, only the symmetrical fault current is calculated. Values of the symmetrical fault current are included in Tables I, II, and III, and give the currents from the first quarter cycle to 3 sec after short circuit. The values have been plotted to give the curves of Fig. 2. The curves of Fig. 4 were obtained in a manner exactly similar to that described for Fig 3 above.

Appendix II—Sample Problems

The following problems will be solved to illustrate the correct use of the decrement curves and tables. The system considered is represented by the one line diagram, Fig. 9, with a dead short circuit occurring at point x. The maximum short circuits are calculated assuming the system loaded and all generators operating. The minimum short-circuit currents are calculated considering generators 1 and 2 only, their excitations corresponding to no load. When no automatic voltage regulators are used, compute:

1. The maximum short-circuit current for a 3-phase fault 0.50 sec after fault.
2. The maximum short-circuit current for a line to line fault 0.50 sec after fault.
3. The maximum short-circuit current for a line to ground fault 0.50 sec after fault.
4. The minimum short-circuit current for a 3-phase fault 0.50 sec after fault.

Assuming that generators 1 and 2 are equipped with voltage regulators, the ratio of exciter ceiling voltage to rated voltage when delivering full load being 130 per cent, calculate the sustained short-circuit current for a 3-phase fault. Consider the generators loaded previous to fault.

Procedure

a. Determine the capacity of the equivalent generator.

b. Calculate the reactance to fault, x_f, as a percentage on the equivalent generator kilovoltampere capacity.

c. Estimate or calculate the open circuit time constant T_{doe}' of the equivalent generator.

d. Determine the proper time t to use on the curves, using the equivalent generator open circuit time constant and the desired time in seconds.

e. Obtain the short-circuit current in the fault from the curves or tables, using the reactance to fault and the corrected time from *b* and *d* above.

Solution 1. Fig. 1 or Table IV

a. Equivalent generator capacity is the total system kilovoltamperes and equal 90,000 kva.

b. Reactance to fault $x_f = x_1$

$x_1 = 1/I'' = 1/10.39 = 0.0964$ on 20,000-kva base, from Fig. 10 $= 0.434$ or 43.4 per cent on 90,000-kva base.

c. For a first approximation, assume $T_{doe}' = 5.0$ sec.

d. Correct time to use on curves equals 0.50 sec. (No correction when $T_{doe}' = 5$ sec.)

e. From Fig. 1, or interpolating from Table IV, using $x_f = 43.4$ per cent, $t = 0.50$ sec, $I_{sc} = 1.84 \times 90{,}000/60\sqrt{3} = 1{,}590$ amp, *answer*.

More accurate results are obtained by calculating T_{doe}' from eq 1, using Fig. 10.

$$T_{doe}' = \frac{1}{1/2.96 - 1/8.96}\left[3.8(2.30 - 0.30)\left(\frac{0.386}{2.96}\right)^2 + 5.5(0.80 - 0.136)\left(\frac{1.114}{2.96}\right)^2 + 6.0(0.685 - 0.114)\left(\frac{0.90}{2.96}\right)^2 + 5.0(1.10 - 0.18)\left(\frac{0.56}{2.96}\right)^2\right] = 4.98 \text{ sec}$$

(In this particular case, the correction in time is too small to warrant attention from a practical standpoint.)

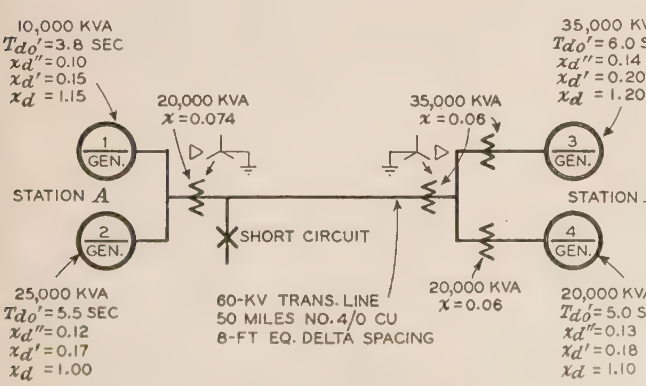


Fig. 9. Typical system used in sample problems

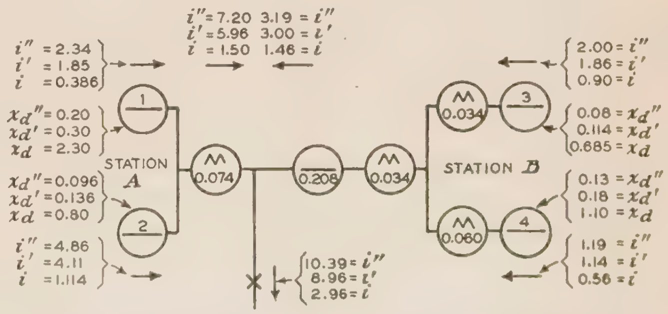
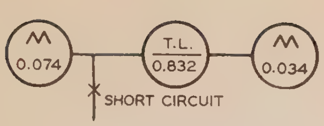


Fig. 10. Diagram of positive and negative sequence network reactance, and positive sequence current distribution

Per unit values on 20,000-kva base
(Assumes generator $x^2 = x_b''$)



Per unit values on a 20,000-kva base
Assumed transmission line $x_0 = 4.0x_1$)

Fig. 11. Diagram of zero sequence network reactance

SOLUTION 2. FIG. 1 OR TABLE IV

The solution for a line to line short circuit is similar to that outlined above with the following exceptions:

b. Reactance to fault $x_f = 2x_1 = 2 \times 43.4 = 86.8$ per cent on 90,000-kva base.

e. From Fig. 1 or Table IV, using: $x_f = 86.8$ per cent, $t = 0.50$ sec, $I_{sc} = 1.02 \times \sqrt{3}[90{,}000/60\sqrt{3}] = 1{,}530$ amp, *answer.*

SOLUTION 3. FIG. 1 OR TABLE IV

Again the solution is similar, but with the following exceptions:

b. Reactance to fault $x_f = 2x_1 + x_0$

x_0 = equivalent reactance of 0.074 and (0.832 + 0.034) in parallel
= 0.0682 on 20,000-kva base, from Fig. 11
= 30.7 per cent on 90,000-kva base

$x_f = (2 \times 43.4 + 30.7) = 117.5$ per cent on 90,000-kva base.

e. From Fig. 1 or Table IV, using: $x_f = 117.5$ per cent, $t = 0.50$ sec, $I_{sc} = 0.77 \times 3[90{,}000/60\sqrt{3}] = 2{,}000$ amp, *answer.*

SOLUTION 4. FIG. 4 OR TABLE III

a. Equivalent generator capacity is 35,000 kva.

b. Reactance to fault from station $A(x_f) = (x_1)$.

$x_f = 1/I''_A = 1/7.2 = 0.139$ on 20,000-kva base
= 24.3 per cent on 35,000-kva base. (See Fig. 10.)

c. Since there is no reactance between the generators and the point where they are paralleled, use eq 3.

$$T_{doe}' = 3.8 \times \frac{10{,}000}{35{,}000} + 5.5 \times \frac{25{,}000}{35{,}000} = 5.02 \text{ sec}$$

d. $t = 0.50 \times 5/5.02 = 0.50$ sec, approximately.

e. $I'' = 7.2[20{,}000/60\sqrt{3}] = 1{,}385$, instantaneous symmetrical short-circuit current in amperes.

From Fig. 4 or Table III, using the above values, $I_{sc}/I'' = 0.585$. $I_{sc} = 1{,}385 \times 0.585 = 810$ amp, *answer.*

For the case of voltage regulators procede as follows.

a. Equivalent generator equals 35,000 kva.

b. Reactance to fault equals 24.3 per cent on 35,000 kva.
The above values are obtained from preceding solutions.

Interpolating from Table I, $i = 1.72$.

$$I_{sustained} = 1.72 \times 130/100 = 2.23$$
$$= 2.23 \times 35{,}000/60\sqrt{3} = 752 \text{ amp, } \textit{answer.}$$

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Reactance and Stray Losses of Power Transformers

In this paper are discussed some of the problems of the transformer design engineer in regard to the effect of different winding arrangements, and some of the means employed to predetermine transformer reactance and to keep stray losses at a minimum. A reactance model has been developed to assist the transformer design engineer in checking reactance and stray loss calculations.

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POWER TRANSFORMERS of the present day are required to meet many varied and complicated requirements as a result of which the transformer design engineer is faced with many difficult problems. This paper discusses some of these problems, dealing mainly with the reactance and stray losses of interleaved coil shell type transformers. A discussion is given of the accepted tolerances for transformer reactance and what these tolerances mean to the operator and the designer. Various methods of obtaining uniform reactances on transformer taps are described. The advantages of subdivided conductors in interleaved coil designs are shown. Stray losses in 3-winding transformers under certain load conditions present special problems in all designs.

A reactance model has been developed to analyze reactance formulas experimentally. It consists of power transformer core and coils constructed on a small scale so that various sizes of coils and core openings may be assembled and tested experimentally. It is to the design engineer what the calculating board is to the transmission engineer. The use of this model has enabled the design engineer to keep reactance and stray loss calculations and measurements in pace with other transformer developments.

REACTANCE

The inherent reactance of a power transformer usually is referred to, in practical terms, as "reactance drop." Defined by A.I.E.E. Standards (Rule 13–116) it is the voltage drop in quadrature with the current. The operating engineer is con-

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cerned mainly with the effect of transformer reactance on voltage regulation, its influence on the load division of transformers connected in parallel, and its effect in limiting short-circuit currents. The design engineer in working out the problems of meeting a specified reactance is concerned with the effect on the proportions of the design (*e. g.*, the ratio of copper, insulation, and iron) and the mechanical stresses within the windings under short-circuit conditions. Both operating and design engineers are concerned with the cost of obtaining a desired reactance, and its effect on the practicability of the design.

Several years ago a joint committee of National Electric Light Association and National Electric Manufacturers Association representatives formulated a rule for standard tolerances for transformer impedance (Rule TR6-28 N.E.M.A. Standards) a rule which from the standpoint of the power transformer engineer is virtually a reactance tolerance because of the negligible effect of resistance on the difference between reactance and impedance. The rule provides a tolerance of plus or minus 7.5 per cent for 2-winding transformers, and 10 per cent for autotransformers or transformers with 3 or more windings. These tolerances were arrived at after a comparison of the calculated and tested reactances of practically all designs made for about 3 years preceding the formulation of the rule. They represent what the manufacturer can guarantee without materially increasing his costs (by virtue of having to make changes in design, after tests are made). The determination of reactance in a transformer design is not a precise calculation, because it involves reactance paths and magnetic fields difficult to calculate accurately. Slight variations in manufacture also will cause appreciable differences in reactance, so that it is necessary to have a tolerance factor for this feature of a design. Like most tolerance standards, the N.E.M.A. rule represents a compromise of 2 opposite interests: that of the user of the apparatus who requires adherence to a specified performance in order to plan and operate his system successfully; and that of the manufacturer who should not take undue risks in making guarantees that the development of the art indicates are unsafe or unreasonable.

It is obvious that in order to enhance his position in the industry the manufacturer will do everything within his power to build transformers that have as nearly as possible the specified reactances. The object of this paper is to discuss (1) some of the problems of the design engineer in regard to the effect of winding arrangement (particularly of shell type transformers) required for various types of designs, and (2) some of the means employed to predetermine the reactance and to keep the stray losses to a minimum.

In power transformers of the shell type the windings are interleaved with groups of coils forming what are known as 2 H-L, 4 H-L, or 6 H-L designs indicative of the number of spaces between high and low voltage windings across which leakage flux is set up under load conditions (see Fig. 1). In a simple 2-winding transformer without taps the turns are distributed evenly within the groups as shown in Fig. 1. In such transformers the calculation of reactance and stray losses is fairly simple. Reactance formulas have been developed, by both analytical and empirical methods, which give very satisfactory results. When the transformer has a large portion of winding tapped out, as in designs for tap changing under load, or furnace transformers the problem of reactance becomes more complicated. It is desirable to have the reactance on all taps approximately the same.

In analyzing an interleaved coil design for reactance calculations, the first step is to divide it into groups of ampere turns. A picture of the relative field intensity for the magnetomotive force produc-

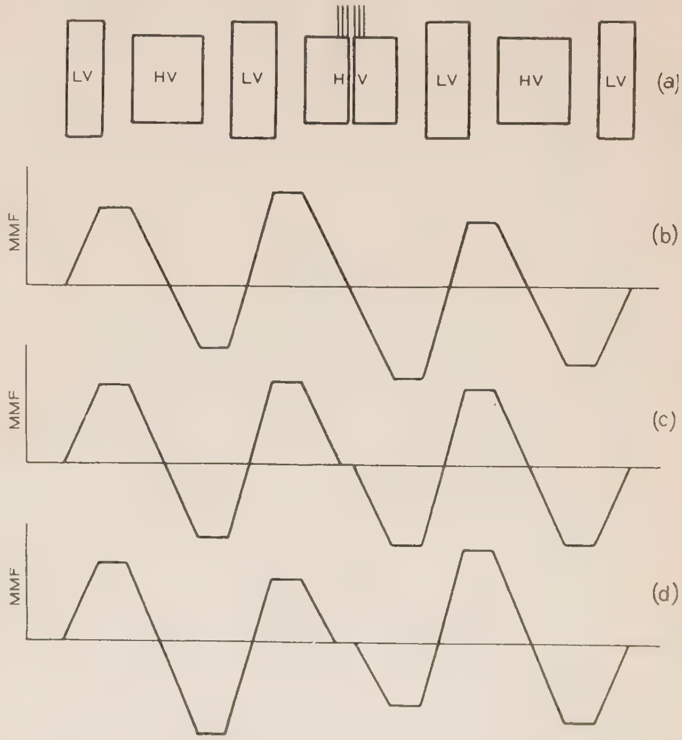

Fig. 2. Arrangement of coils (a) in a 6 H-L interleaved coil shell type transformer with 4 5-per cent taps in the high voltage winding, and magnetomotive force diagrams with (b) all taps in; (c) winding in normal position; (d) all taps out

The reactance is proportional to the sum of the squares of the magnetomotive forces across the H-L spaces; variation from mean reactance is less than 3 per cent of the normal reactance

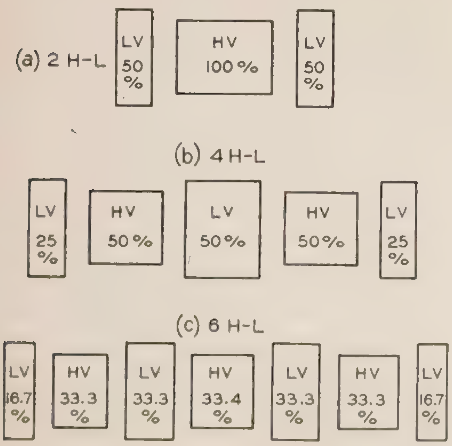

Fig. 1. Horizontal cross sections of interleaved coil shell type transformers without taps, showing simplest arrangements of coil groups

Figures represent per cent of total turns; H. V. and L. V. represent high and low voltage coils, respectively

ing leakage flux at various points along the axis of the windings may be obtained by plotting the total ampere turns against distance, or length of winding (see Fig. 2). Each group is analyzed separately, and the reactance voltage drops of all groups are added arithmetically to obtain the total drop. When a large portion of winding is tapped out in one group the reactance on different taps will vary approximately as the sum of the squares of the ampere turns at each H-L space, as shown in Fig. 2. In order to make the reactance as nearly as possible the same on all taps, it is desirable to place the taps in the center of one of the groups, or at the outside of the 2 end groups, where the leakage flux is at or nearly zero. In this location the idle coils do not contribute to the copper loss as they would if they were in a strong leakage field. Figure 2 shows an arrangement of a transformer with 6 H-L groups with the taps in the middle high voltage group, and Fig. 3 with the taps in the outside of the low voltage grounded end groups. In both these designs the variation in reactance on taps is small. For Fig. 2 the reactances on the extreme taps will not deviate more than 3 per cent (plus or minus) from the mean reactance.

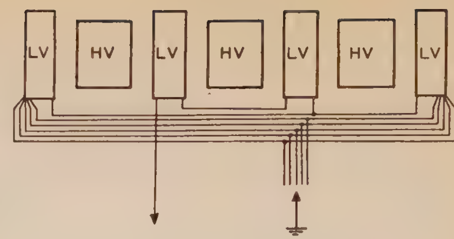

Fig. 3. Interleaved coil design of shell type transformer with taps in the grounded neutral of the low voltage winding

Taps are placed in the end groups to minimize the variation in reactance

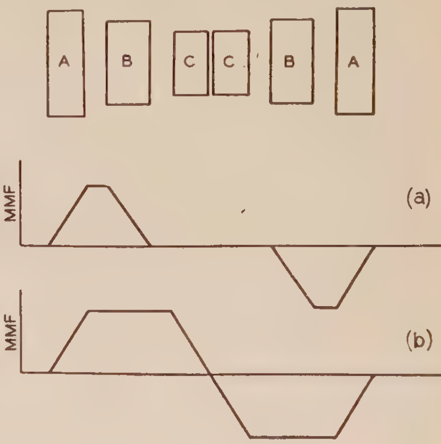

Fig. 4. Horizontal cross section of a 3-winding transformer with magnetomotive diagrams (a) when winding C is idle and (b) when winding B is idle

Under condition (b) the entire winding B is in a strong leakage field, and comparatively high stray losses are produced in it

Methods Used to Vary Reactance

The reactance of a transformer varies directly as the square of the number of turns; it also varies with a factor depending upon the physical dimensions of the coil group, the length of mean turn of the windings, the space between high and low voltage windings and (in the case of an interleaved winding) the number of interleavings or H-L groups. Generally speaking, the higher reactance transformer will have a higher copper loss and lower iron loss, although there are methods of compensating for these effects, as described later in this paper. Special transformers having high reactance, such as grounding transformers, are designed to operate for periods of a minute or 2 at comparatively high leakage flux densities without excessive heating in the windings. Other types of design require low reactance, such as transformers for single-phase railway operation and testing transformers for use in heavy power tests. All the methods mentioned may be used to obtain a reactance differing from that of a normal design; variations in coil dimensions and interleavings are used to obtain large departures from a normal design, while changing the total turns will change the reactance over the ordinary range required.

Methods Used to Keep Stray Losses Minimum

Large power transformers require the use of rectangular conductors of substantial width and thickness in order to obtain sufficient mechanical strength to handle the coil during manufacture and to support the winding against the heavy forces set up during short-circuit conditions. For the past 8 years the practice of subdividing conductors in interleaved shell type windings has been in general use and has contributed largely to the high efficiencies obtained in this type of design. (See "Subdivided Conductors in Shell-Type Transformers," by R. L. Brown, *Electrical Journal,* March 1933.) The stray losses in an interleaved design vary directly with the square of the width of the conductor. With the subdivided conductor it is possible to wind coils with 2 or more narrow conductors ($^1/_8$ to $^1/_4$ in. wide) side by side and obtain a coil that is fully as strong as the older type of coil (with conductors $^1/_4$ to $^1/_2$ in. wide) and even better mechanically from a manufacturing standpoint. Transpositions in the parallel conductors are made either physically near the center of the coil or by electrical connections at the coil ends, in order to place each conductor in a uniform leakage field and obtain full advantage of the subdivision of the winding.

Compared with the older type of single conductor winding, the subdivided winding with 2 half-width conductors side by side will reduce the total stray losses of the transformer 75 per cent. Practically it is more economical to use subdivided conductors of greater than $^1/_2$ the width of the former solid coils. This results in fewer coils, better space factor of winding, and a reduction in stray losses of 25 to 50 per cent. Actual tests have proved that such coils, which are thicker and heavier than the former single-conductor coils, have higher strength to withstand short-circuit currents.

The problem of stray losses in 3-winding transformer design requires careful consideration. In all 3-winding transformers, regardless of whether they are of the core or shell type, there are some conditions of operation in which the leakage flux set up by the operation of 2 windings as a primary and secondary will produce stray losses in the third, or idle winding. Figure 4 shows a simple arrangement of coils in a 3-winding transformer. The

sketch represents either a horizontal cross section of coils through the "window" of a shell type transformer, or a vertical section through the "window" of a core type transformer. When windings A and B, or B and C, are operated together, the third winding has little or no loss in it; but when A and C are operated as primary and secondary, the third winding (B) is entirely in a strong leakage field, and has comparatively high stray losses. This is particularly true if the windings all have the same or nearly the same kilovoltampere capacity. This coil arrangement in shell designs ordinarily is used only when A is a tertiary winding of not more than $^1/_3$ the capacity of the other windings; in this case the magnetomotive force shown in Fig. 4b is only $^1/_3$ as great and the stray losses in the middle winding (B) are not high. The use of subdivided conductors in this connection keeps the stray losses at a minimum.

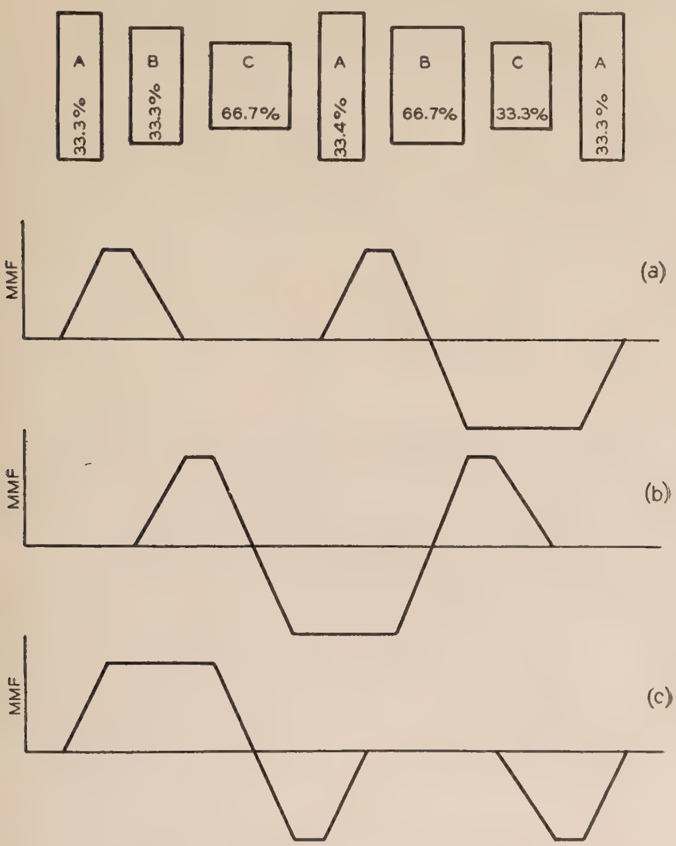

Fig. 5. Three-winding interleaved shell type transformer with equal reactances, and magnetomotive force diagrams for (a) winding C idle; (b) winding A idle; (c) winding B idle

Not more than $^1/_3$ of the idle winding is in a strong leakage field, in any case; hence stray losses are comparatively low

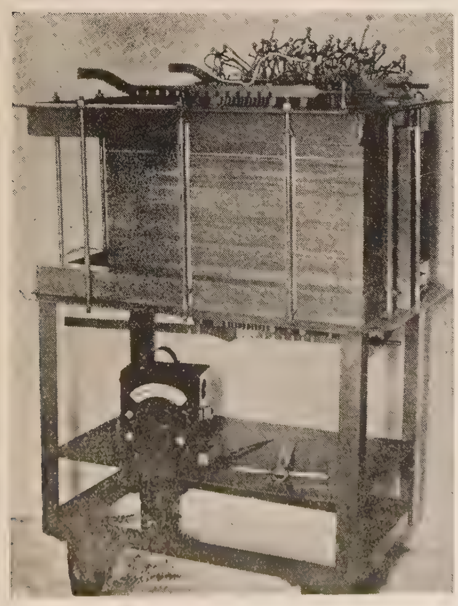

Fig. 6. Model of core and coils of a shell type transformer for predetermining transformer reactances

A method of equalizing stray losses in 3-winding, shell type transformers with windings of equal output is shown in Fig. 5. In this arrangement each pair of windings is located so as to provide a 3 H-L arrangement; and in no condition of operation is more than $^1/_3$ of the idle winding in a strong leakage field. This disposition of windings has been used many times not only to produce low stray losses but also to give substantially equal reactances A to B, A to C, and B to C.

Use of Reactance Model

Several years ago the idea was conceived of using a small scale working model of a transformer core and coils, to predetermine reactance. Figure 6 shows such a model of a shell type transformer. It is built with linear dimensions $^1/_5$ of those of a 20,000-kva transformer. Coils of scale dimensions approximating those of large transformers may be assembled quickly on the core of this model and the impedance and reactance measured. The core is made similar to the regular shell type magnetic circuit, except that at one end joints are butted instead of interleaved. With this arrangement the coils may be assembled without dismantling the core, and the length of the openings or "windows" of the core may be adjusted to any desired length. Steel structural parts are made in proportion to those in commercial designs so that data on stray losses under load conditions may be obtained. Coils of various widths and of various numbers of turns are employed to permit winding combinations having physical dimensions and constants corresponding to nearly all sizes and arrangements of shell type power transformer windings.

As an example of the usefulness of the reactance model, the winding for a 20,000-kva transformer on order was set up on the model core to check the reactance calculations. The transformer was required to operate in parallel with another unit having 7.13 per cent reactance on the normal voltage tap. When built, the new transformer tested 7.12 per cent by actual measurement (calculated to be 7.16 per cent by the use of the model); for the lowest voltage tap the transformer tested 7.63 per cent (calculated to be 7.66 per cent). Such results are within the errors of measurement. It is not expected that such close agreement always can be obtained, but this example is given to illustrate the effectiveness of the model.

The reactance model is to the transformer engineer in a large degree what the calculating board

is to the transmission engineer. Theoretical formulas for reactance and stray losses readily are checked and special reactance investigations quickly are made with the model. A transformer design with windings unsymmetrical with respect to number of turns, or coil dimensions, or both, may be investigated for reactance and stray losses before the transformer is built. Unusual dimensions of coil groups, which might otherwise involve some risk because of lack of test data to confirm theoretical formulas, readily are checked. The division of load currents in 3 or more paralleled windings, in a transformer in which all the windings are not exactly symmetrical, can be determined experimentally with the model in a fraction of the time required to make all the calculations that otherwise would be required. The model is very useful in the investigation of reactance constants and stray losses of 3-winding and autotransformers.

Power transformers of the present day are required to meet many complicated conditions. Surge-proof insulation, voltage, and phase-angle control by tap changing under load, double-secondary and 3-winding designs, autotransformers with tertiary windings—these are some of the features that have made reactance and stray loss calculations more complicated. The transformer engineer has kept reactance and loss design formulas in step with new requirements. The reactance model is an important aid in this progress, and its use has accomplished much to keep this branch of the art abreast of other developments.

Irregular Windings in Wound Rotor Induction Motors

The importance of using regular windings in polyphase wound rotor induction motors is stressed in this paper. Harmful effects upon the efficiency, power factor, breakdown torque, and noise of the motor may result with an irregular winding, due to differential leakage. The Goerges diagram of tooth fluxes is presented for studying this phenomenon. Means of avoiding trouble of this sort also are pointed out. It is further observed that 3-phase motors having a number of poles which is a multiple of 6 are most likely to be troublesome.

By

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IT IS generally appreciated that the most advantageous number of slots for induction motors is one that is divisible by the product of the number of poles and phases. With this arrangement, the windings can be distributed uniformly and regularly all around the circumference, and all undesirable irregularities in both the electric and magnetic circuits are avoided. However, on account of the many phase and pole combinations required in practice, and the expense incident to a large number of different dies and the stock-keeping problems arising from too many different slot combinations, it has frequently been found expedient and economical to depart from the most ideal combination. A great many motors in which the number of slots per pole per phase is not an integral number have been built and have given satisfactory performance, but the indiscriminate use of irregular windings, particularly in wound rotor motors, carries with it certain dangers and at times leads to very unsatisfactory results.

The following example illustrates this point. Two rotors were built for a one-horsepower 6-pole 3-phase wound-rotor induction motor having 36 stator slots, one rotor having 27 slots and the other having 24. The designs were in general very similar, but on test it was found that the 24-slot rotor gave a very much inferior performance; in fact, much more so than indicated by the regular routine calculations for the slight difference in rotor slots. Such calculations indicated approximately a 10 per cent difference in the breakdown torque, but it was found that the 27-slot rotor in reality developed a breakdown torque 42 per cent higher than that developed by the 24-slot rotor. A more careful analysis of the designs indicated that this great difference must have been due to the very much larger differential leakage in the 24-slot rotor which is caused by the irregularities in the secondary winding and for which allowance is not made in conventional leakage calculations.

Causes of Differential Leakage

As has been developed in several previous publications (see list at end of paper, particularly refer-

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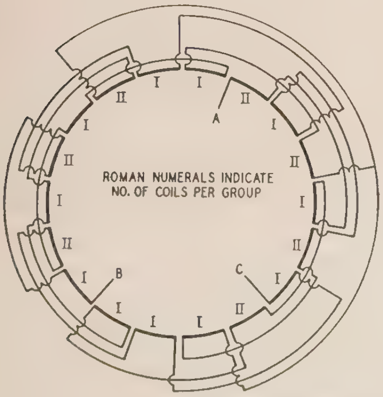
1. For all numbered references see list at end of paper.

ences 1, and 4–8) differential leakage exists whenever the winding distribution of the secondary member does not properly match the winding distribution of the primary member for any, or all, of the rotor positions. Whenever this is the case, it is not possible for the secondary tooth fluxes or magnetomotive forces to balance exactly at all points the primary tooth fluxes or magnetomotive forces even though a short-circuited secondary without resistance or reactance is assumed. In ordinary polyphase induction motors, the matching of the 2 members is obtained only when the stator and rotor have the same number of phases and the same coil throw and also when the rotor is in such a position that its phase belts line up exactly with the phase belts of the stator. As soon as the rotor is moved to any other position, differential leakage is obtained. Also in all cases where the number of phases or the coil throw of the rotor differs from the stator, differential leakage is present. This effect is the conventional "belt leakage" as it was first called by Adams,[1] and various means for allowing for it are given in literature.[5]

Considering that the fundamental nature of differential leakage is as indicated above, it is at once evident that if one member has a winding with a distribution irregular to a greater or lesser degree, even if the winding distribution of the other member is regular, the matching of the 2 windings will be imperfect to a greater or lesser degree and usually more so than in cases where both members have regular windings. It follows directly, then, that greater amounts of differential leakage effects are to be expected.

Importance of Differential Leakage

The practical importance of such conditions has already been indicated by the reference to the breakdown torque previously given, but some additional experimental data may be of interest. In further consideration of these data, it should be kept in mind that, while both rotor windings are irregular, they are irregular to a very much different degree. The 27-slot winding, with $1^1/_2$ slots per pole per phase, permits a layout giving absolutely balanced secondary voltages with proper 120-deg phase displacement. Such a layout can be obtained by the "least-common-multiple" method of tabulation due to Tingley.[9] On the other hand, the 24-slot winding cannot be made to give perfectly balanced secondary voltages. However, it is possible to lay out a winding to give approximately balanced voltages. Such a winding is shown in Fig. 1, and the voltages induced therein are indicated in Fig. 2. Expressed in terms of symmetrical components, and based upon a positive phase sequence voltage of 100 per cent, the negative phase sequence voltage is only 2.8 per cent and the zero phase sequence voltage is only 4 per cent. In spite of such small dissymmetry, it has been found that windings of this nature (12-pole 48-slot windings are equivalent and have been used extensively) when used in smaller squirrel-cage motors, have given generally satisfactory results. While a slight unbalance in the stator currents and certain damping currents in the rotor cause some additional losses, the efficiency is only slightly affected thereby. The damping currents of the rotor, on the other hand, largely eliminate irregularities in the fluxes, and consequently differential leakages, and their harmful effect on power factor and breakdown torque are largely avoided. This, however, is not the case when such an irregular winding is used in either the primary or the secondary in combination with another phase-wound member, even if that member has a regular winding, and as a result, unsatisfactory performance is obtained. Further comparative test data on the locked reactances obtained with the 2 rotors are given in Table I.



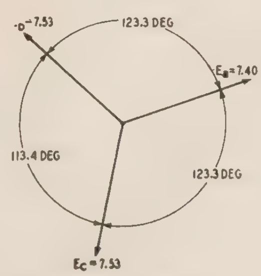


Fig. 1 (left). A 3-phase 6-pole 24-slot winding

Fig. 2 (right). Voltages induced in the 3-phase 6-pole 24-slot winding, shown in Fig. 1

Table I—Test Data on Locked Reactances

Method of Measurement	27-Slot Rotor	24-Slot Rotor
1. A locked reading at 220 volts (normal voltage), 60 cycles, using total watts input and average amperes	5.95 ohms	7.4–7.7 ohms
2. A locked reading at 40 volts, measuring watts per phase and voltage to neutral		7.48–9.65 ohms
3. Calculated from observed breakdown torque (see reference 10) at 220 volts, 60 cycles	6.6 ohms	9.85 ohms
4. Locked readings at 200 volts, 300 cycles, measuring watts per phase and voltage to neutral	40–41 ohms	54.0–72.7 ohms

Of the locked reactances, probably the most reliable are those calculated from the breakdown torque and these show the average reactance with the 24-slot rotor is 49 per cent higher than that with the 27-slot rotor. But even more enlightening are the curves shown in Fig. 3, which give the reactances of the individual stator phases for various rotor positions with both rotor windings. Briefly, these curves were taken as follows: The secondary was short-circuited and a balanced 3-phase 300-cycle electromotive force of 200 volts was impressed on the stator. Meters were inserted in the stator phases to measure phase volts, watts, and amperes. Readings were then taken every 10 mechanical degrees throughout a complete revolution of the rotor. This interval, which corresponds to a stator slot pitch,

was sufficiently small because it was found that on account of the rotors being skewed, the variation in zig-zag leakage through a slot pitch was negligible. The reactances thus obtained were proportioned down to equivalent 60-cycle reactances based upon the assumption that 6.6 ohms at 60 cycles is proportional to 40.5 ohms at 300 cycles. The following experimental facts shown by the curves in Fig. 3 should be carefully noted:

1. When the 24-slot rotor is used, the short-circuit reactance of each stator phase varies cyclically as the rotor is turned through a pole pitch. Moreover, this reactance is always larger than that with the 27-slot rotor, ranging, in fact, from 133 to 179 per cent of the average reactance obtained with the latter.

2. At no position of the rotor are the leakage reactances of all 3 phases equal to each other, but the reactance of each phase, as the rotor is revolved, goes through its own cycle which is displaced 60 electrical degrees from the reactance cycles of the other 2 phases.

3. Qualitatively, statement 2 holds for the 27-slot rotor as well as for the 24-slot rotor, but the variation is so small as to be of little practical significance and probably would not ordinarily be detected.

Two important differences between the belt leakage obtained with regular windings and the differential leakage evident in Fig. 3 are that, in the former cases, the leakage reactances of the stator phases are balanced at all times and the reactances of all the phases simultaneously vary cyclically throughout a phase belt. Neither of these conditions holds in our case.

From these figures it can be seen readily that the irregularity of the 24-slot winding introduces such a large amount of differential leakage as to seriously affect motor performance. In Fig. 4, comparative brake tests with the 2 different rotors are given. With the 27-slot rotor, the brake test was taken at 220 volts; with the 24-slot rotor, the brake test was taken at 253 volts, which was the voltage found necessary in order for the 24-slot rotor to develop the same breakdown torque as the 27-slot rotor. A slight advantage in efficiency, particularly at light loads, and a conspicuous advantage in power-factor at all loads, is noted for the 27-slot rotor.

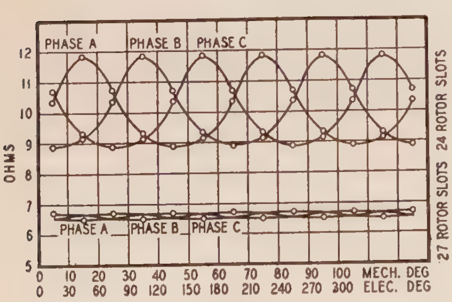


Fig. 3. Leakage reactance comparisons with the 27-slot and 24-slot windings, in various rotor positions

Moreover, noise measurements showed the 27-slot rotor to be 6 decibels quieter than the 24-slot rotor.

Methods of Analyzing Irregular Windings

In view of the great practical importance which differential leakage may assume in certain cases of irregular windings, the designer is, of course, interested in having at his disposal means for analyzing irregular windings so as to avoid those leading to unsatisfactory performance. Unfortunately, the correct quantitative analysis for this purpose would be very complicated. Certain diagrams developed by Goerges and a method given by Hellmund showing their application to the study of differential leakage offer useful tools in connection with a study such as the one given in this paper. (See references, particularly 4 and 5.)

Briefly stated, the Goerges diagrams are vector diagrams indicating the magnetomotive forces set up in the various teeth. In Fig. 5c is a Goerges diagram constructed for the stator winding and which may be used to illustrate the quickest method of constructing such a diagram. The stator winding was chorded one slot and therefore the currents and magnetomotive forces in the top and bottom coil sides in the various stator slots are as given in 5a. The magnetomotive force acting across the slot due to any coil side can be represented by one of the 3 unit vectors in 5b. Starting from any arbitrary point such as P in Fig. 5c, a vector is laid off to represent the total magnetomotive force acting across the slot. In the chosen case, for slot 1, this vector is twice the unit vector A in Fig. 5b. From the end of this vector, the magnetomotive force acting across the next slot, and so on, is laid off until the diagram closes upon itself. It can be readily shown that the vectors from the center of the figure to various points of the circumference represent the magnetomotive forces acting upon individual teeth.[3,7]

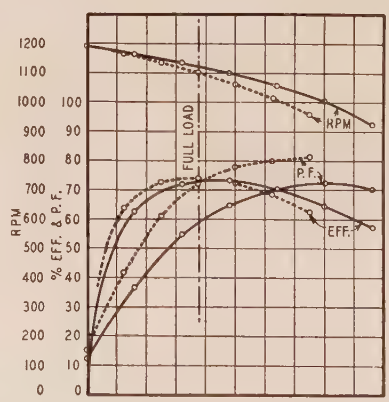


Fig. 4. Comparative brake tests with 27-slot and 24-slot rotors

Solid lines—24-slot rotor performance
Dotted lines—27-slot rotor performance

If the primary had been wound full pitch, instead of chorded, the Goerges diagram would have been the regular hexagon shown in heavy, solid lines in Fig. 6. If the secondary winding is also 3 phase, full pitch, with an integral number of slots per pole per phase, its Goerges diagram is likewise a regular hexagon. If, in addition, the secondary phase belts are exactly opposite the primary phase belts, the secondary diagram coincides exactly with that of the primary and there is no differential leakage. If, on the other hand, the secondary is shifted one-half a phase belt, its hexagon is shifted by a similar amount and takes the position shown by the heavy dotted lines in Fig. 6. The magnetomotive forces (radius vectors) for the individual points of the circumference are no longer alike in all cases, and as a consequence, differential leakage is obtained. The shaded areas

n Fig. 6 are an indication of the amount of differ-
ntial leakage to be expected. It can be readily seen hat the differential leakage for all relative positions of the primary and secondary would be avoided if ooth the primary and secondary diagrams were found o be a circle, a condition which, of course, can be obtained only with an infinite number of phases and lots in both members.

Goerges Diagrams Should Approach a Circle

While the actual amount of differential leakage s governed by the relation of the diagrams of the orimary and secondary member to each other, as ndicated by the shaded areas in Fig. 6, it is possible o obtain a fairly good idea of the merits of each of he individual windings with reference to differential eakage by comparing its diagram with a circle of about equivalent area. In general, it can be said

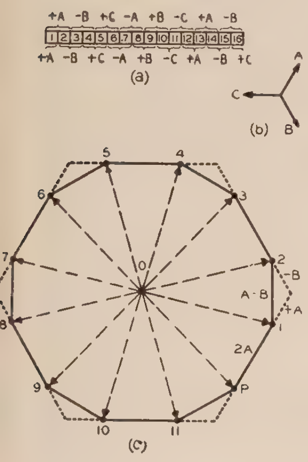


Fig. 5 (left). Diagrams for the stator winding, 36 slots, 6 poles, 3 phase, coil throw 1–6

a. Arrangement of coils in slots b. Unit vectors c. Goerges diagram

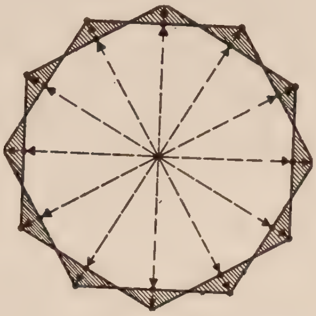
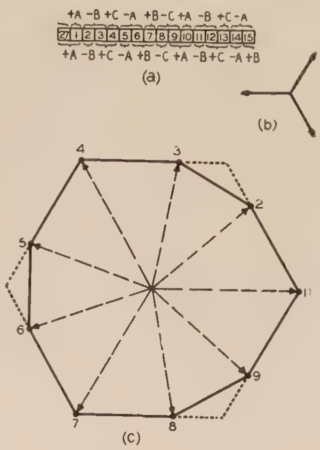


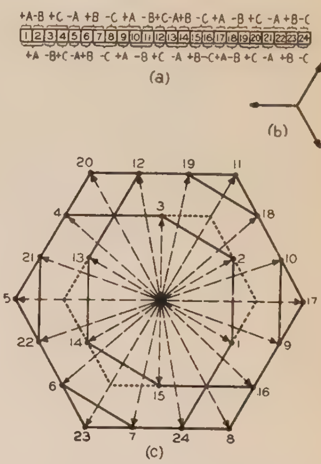
Fig. 6. Differential leakage fluxes with 2 full pitch 3-phase windings

hat the more nearly the Goerges diagrams of the stator and rotor approach a circle, the less differen-ial leakage there will be. Constructing the Goerges diagrams for the 27-slot and 24-slot rotors after the fashion of Fig. 5, we obtain the diagrams (full lines) given in Figs. 7 and 8. From these figures, it is at once evident that the results in the 2 cases should be very different. The diagram of Fig. 7, applying to he 27-slot combination, does not depart from the circle appreciably more than does the hexagon apply-ng to a full-pitch 3-phase winding indicated by the dotted lines.

The extreme irregularity of the diagram in Fig. 8 applying to the 24-slot arrangement, however, ndicates plainly why large differential fluxes are ob-ained. The reason why the leakage varies cycli-cally throughout a pole pitch is indicated also on Fig. 8. The diagram does not close after a single pair of poles has been traversed, but closes only after he entire 6 poles of the winding have been traversed. Consider any one position of the rotor and take note of all the rotor tooth fluxes with reference to some arbitrarily chosen tooth of the stator. Now let the rotor revolve slowly until a condition is obtained where the tooth fluxes of the rotor occupy exactly the same position with respect to the previously selected stator tooth. The failure of the Goerges diagram to close until the entire rotor winding is



a. Arrangement of coils in slots
b. Unit vectors
c. Goerges diagram



a. Arrangement of coils in slots
b. Unit vectors
c. Goerges diagram

Fig. 7 (left). Diagrams for the 27-slot rotor winding, 6 poles, 3 phase, coil throw 1–5

Fig. 8 (right). Diagrams for the 24-slot rotor winding, 6 poles, 3 phase, coil throw 1–5

traversed indicates that this condition will not be obtained until the rotor has turned through one complete revolution. As far as only the rotor winding itself is concerned, we might, therefore, expect the differential leakage to vary cyclically throughout a revolution; but when we consider that each pole of the stator winding is identical with every other pole, we see that, after the rotor has turned through one pole pitch, the rotor tooth fluxes occupy a position with respect to the stator tooth fluxes similar to the starting position and, therefore, the differential leakage should vary cyclically throughout a pole pitch as observed. If, however, the stator winding also had 24 slots and a diagram as given in Fig. 8, we would expect the differential leakage to vary cyclically throughout a revolution. A somewhat similar line of reasoning could be applied to the 27-slot rotor to show why its differential leak-age also varies cyclically throughout a pole pitch; except that, in this case, no matter how irregular a winding distribution were used on the stator, the differential leakage cycle could not take more than a pair of pole pitches to complete itself because the Goerges diagram for the rotor closes after a pair of poles. It is also evident why the reactance cycles of the stator phases are displaced by one phase belt; suppose the rotor to be in a position to give maximum differential leakage in one of the rotor phases, the maximum differential leakage will not be obtained in the adjacent phase until the rotor has moved one phase belt. Thus the Goerges diagrams serve well

to explain the 3 experimental facts to which particular attention was drawn previously.

Goerges Diagrams Can Be Plotted Quickly

As previously mentioned, the actual computation of the differential leakage in the winding just discussed is very difficult and would consume far more time than the design engineer could profitably afford to spend for the purpose. On the other hand, the plotting of the Goerges diagram can be accomplished in a very short time, and if the result is such that the departure of the diagram from a circle is not much different from that for a conventional full pitch winding with an integral number of slots per pole per phase, it can be assumed that the differential leakage will be about equivalent to that obtained with the regular winding. However, if the departure is appreciable, such as indicated in Fig. 8, it is generally advisable in a motor with a phase-wound secondary to change the design to some other combination of slots and windings, and wherever this change is not possible, it should be expected that the motor performance may depart very appreciably from that indicated by ordinary methods of calculation.

Goerges Diagrams of Other Windings

A few words as to the type of Goerges diagram to be expected in other windings may be of interest. Windings irregular in distribution but balanced according to the "least-common-multiple" system of tabulation give a more regular diagram and less differential leakage than other irregular distributions in substantially the same number of slots. Previous mention was made as to the significance of the number of poles required to be traversed before closure of the diagram was obtained. It is desirable that the diagram close after a pair of poles and this condition will be obtained if the number of possible parallels of the winding is equal to the number of pairs of poles. In any "least-common-multiple winding," the number of pairs of poles required for closure of the Goerges diagram is given by the quotient

$$\frac{\text{pairs of poles}}{\text{highest common factor of (No. of slots) and (No. of pairs of poles)}}$$

It should be pointed out that particular heed should be given to those 3-phase windings for which the number of poles is a multiple of 6, as the number of slots into which a balanced winding can be used is very limited. For example, for a balanced 3-phase winding of 6, 12, 24, or 30 poles, the number of slots must be a multiple of 9 and for a balanced 3-phase winding of 18 or 36 poles, the number of slots must be a multiple of 27.

Conclusions

The principal point brought out in this paper is that certain windings with slight phase unbalance which have been used satisfactorily for years on polyphase squirrel-cage motors, may prove entirely unsatisfactory for wound rotor motors due to the unbalanced magnetomotive forces and consequent large amounts of differential leakage. The vector diagrams shown afford a simple means for studying the adequacy of a given winding.

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Transformer Reactance and Losses With Nonuniform Windings

A simplified method of calculating the reactance and eddy current losses of transformers with nonuniformly distributed windings is presented in this paper. The method has been in use for several years and has yielded highly satisfactory results.

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Pittsfield, Mass.

When the ampere turns of the 2 windings of a concentric transformer are distributed uniformly, the leakage flux due to the load current is virtually parallel to the axis (axial) and the reactance and eddy current losses may be calculated accurately by the conventional formulas for concentric windings. When there are large irregularities in the windings of concentric transformers occasioned by

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery. Manuscript submitted Aug. 30, 1933; released for publication Oct. 18, 1933. *Not published in pamphlet form.*

taps, extra end turn insulation, etc., the conventional formulas for concentric windings do not yield accurate results because the leakage flux is no longer parallel to the axis, but has substantial components of cross flux perpendicular to the axis (radial) depending upon the amount of the irregularities.

In this paper, the reactance and eddy current calculations have been resolved into 2 components, one depending upon the axial flux and one depending upon the radial flux; conventional formulas for concentric windings are used for the former, and conventional formulas for interleaved windings for the latter. This method has been in use for several years and has yielded very accurate results; it has greatly simplified and reduced the labor of calculating the reactance and eddy current losses of transformers with concentric windings with large irregularities in the windings.

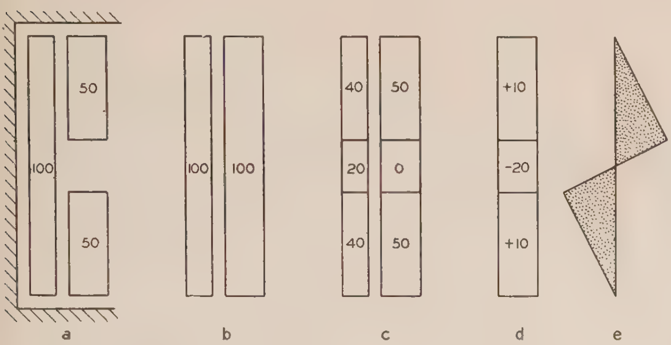


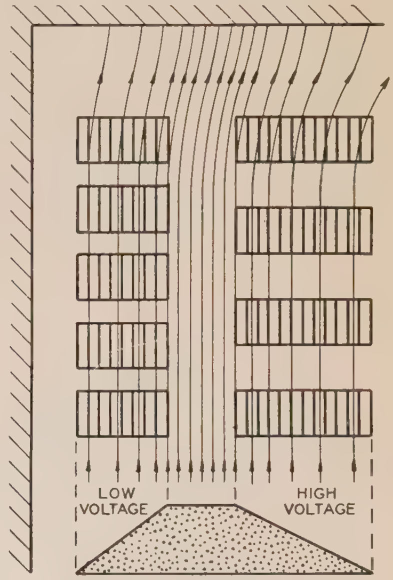
Fig. 1. Diagrams illustrating the calculation of reactance of a simple concentric transformer with taps out of the center of the outside winding

Tap Connections Must Be Designed Properly

For many years it was the practice to specify transformer reactance and losses only on the full winding connections. If the transformer was provided with taps, the reactances on the tap connections seldom were calculated; and if the taps were for full capacity, the losses were considered only to the extent necessary to assure the designer that the transformer would meet its heating guarantee. If transformers are to operate in multiple, it is essential that the reactance on all tap connections involved in multiple operation be within the limits for satisfactory multiple operation; and even though the transformer meets its heating guarantee, it is important that the losses not be increased unduly on the tap connections.

Practical formulas have been available for many years for determining the reactance of transformers with concentric windings when the turns were distributed uniformly axially and also for balanced interleaved windings. If a large part of the windings of a concentric transformer be tapped out at the center, the turns will not be distributed uniformly axially along the 2 windings and the usual concentric reactance formula gives only a rough approximation of the reactance which is always too small a value. It is theoretically possible to calculate the reactance by dividing the windings into several co-axial cylinders and calculating each pair separately. At best this is a time consuming and tedious process. About 8 years ago the author suggested a method of eliminating this extra labor by resolving the reactance calculation of such unbalanced windings into operations involving only the simple concentric and interleaved reactance formulas familiar to all transformer designers.

Fig. 2. Section through a portion of windings of a conventional concentric coil transformer; diagram at bottom shows relative leakage flux densities



The following simple case illustrates the method to be pursued. Figure 1a represents a section through a part of a simple concentric transformer with taps cut out of the center of the outside winding so that the idle space in the center of the outside winding is 20 per cent of its total length. The numbers in the rectangles represent the percentage of the total active winding in each section. The operations necessary for calculating the reactance are as follows:

1. Assume a uniform distribution of turns in the 2 windings as in Fig. 1b. If the over-all lengths of the coils are not the same, use the greater. Calculate the reactance on the basis of this uniform distribution by the conventional formula for concentric winding reactance.
2. Divide each winding into sections and indicate the actual percentage of active turns in each section as in Fig. 1c.
3. Opposite each section set down the difference in percentage turns between the 2 windings, marking this difference positive when the outside winding turns are greater and negative when the inside winding turns are greater, as in Fig. 1d.
4. Call the positive ampere turns primaries and the negative ampere turns secondaries, and calculate an interleaved reactance component from this set-up using the dimensions of the winding with unequally distributed turns and the conventional formula for the reactance of interleaved windings.
5. Multiply this interleaved reactance component by the ratio $\frac{\text{interleaved effective turns}}{\text{total effective turns}}$ in order to convert it into percentage of line voltage. Add this final value to the concentric reactance to obtain the total effective reactance of the transformer.

The same method can be used for much more complicated irregularities such as windings of unequal lengths, taps in more than one place, thinning out of

turns due to extra insulation at the line ends, and inequalities in both stacks. A very useful application of this method is in calculating the reactance between either of 2 interleaved windings and a third concentric winding.

In Fig. 2 is shown a section through a portion of the windings of a conventional concentric coil transformer as used for large units. The lines show the approximate direction of the leakage flux due to the load current in the windings and the flux diagram below shows the relative leakage flux densities. It may be noted that the leakage flux cuts these windings in a direction approximately parallel to the major dimensions of the conductors. Since the eddy current losses in a conductor vary as the square of its dimension perpendicular to the cutting flux, it may be seen that the concentric transformer possesses an important inherent advantage when wound with strands having their greater dimensions axially. Where currents are large, the conductor must consist of several strands in multiple, in which case it is essential that the conductors be so transposed that each will have the proper reactance to carry its share of the load.

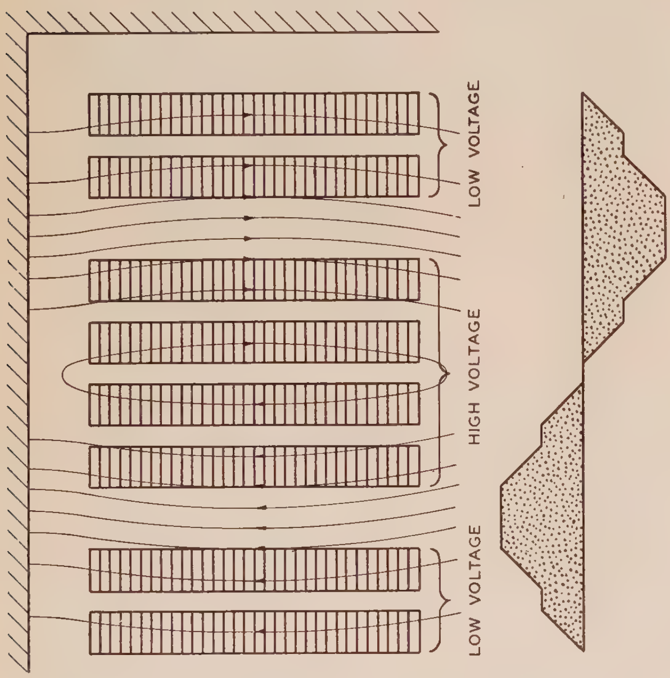


Fig. 3. Section through a portion of windings of a conventional interleaved coil transformer; diagram at right shows relative leakage flux densities

Figure 3 shows a section through a portion of the windings of an interleaved transformer; the lines shows the approximate direction of the leakage flux due to the load current, and the flux diagram shows the relative leakage flux densities. It may be noted that the leakage flux cuts the conductor in a direction perpendicular to the major dimensions of the conductor. This inherent disadvantage is an important handicap in designing very large interleaved transformers because the eddy current losses in those conductors adjacent to the main leakage gap between the 2 windings where the flux density is highest will be very high unless the conductors are made very narrow or laminated and transposed—a distinct disadvantage from a mechanical standpoint.

If a concentric transformer has a nonuniform distribution of its turns in the 2 windings as in Fig. 1a its leakage flux no longer will be virtually parallel to the axis of the windings, but will have a small cross flux component depending upon the irregularity. Figure 1e is a diagram of the relative cross flux densities as determined from the unbalanced turns as shown in Fig. 1d. This cross flux will cut the conductors perpendicular to the maximum dimensions of the strands; and if the unbalance is great, it may cause in addition to increased reactance high eddy current losses, particularly near the tapped out portion where the cross flux densities are greatest. The method used in calculating the reactance due to unbalanced turns is also very useful in calculating cross flux eddy current losses. Exactly the same method of calculation is used as in interleaved transformers familiar to transformer designers, but using the cross flux diagrams as in Fig. 1e.

A study of the diagrams resulting from irregularities in the windings of a transformer will show how it is possible to reduce the cross flux reactance and eddy current losses due to taps. Figure 4a represents a transformer with 20 per cent of the outside winding tapped out, and is a repetition of the diagram in

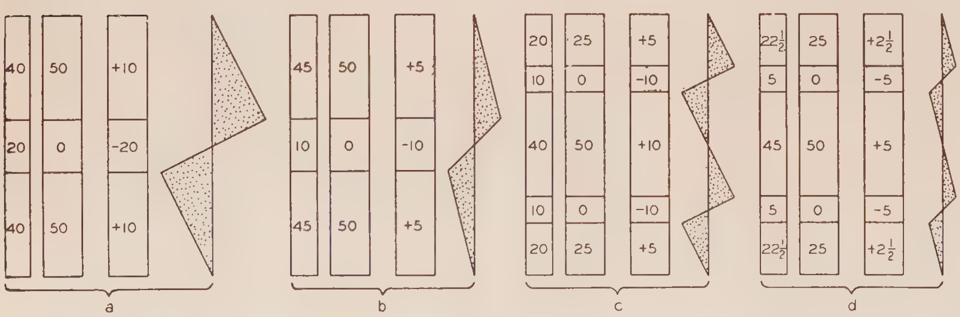


Fig. 4. Diagrams showing how the cross flux reactance and eddy current losses resulting from taps can be reduced by thinning out the turns opposite the tap irregularities

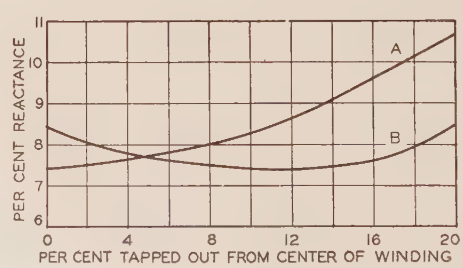


Fig. 5. Reactance of a transformer with 4 5-per cent taps cut from the center of one of the windings (A) compared with (B) that of the same transformer with proper thinning of turns

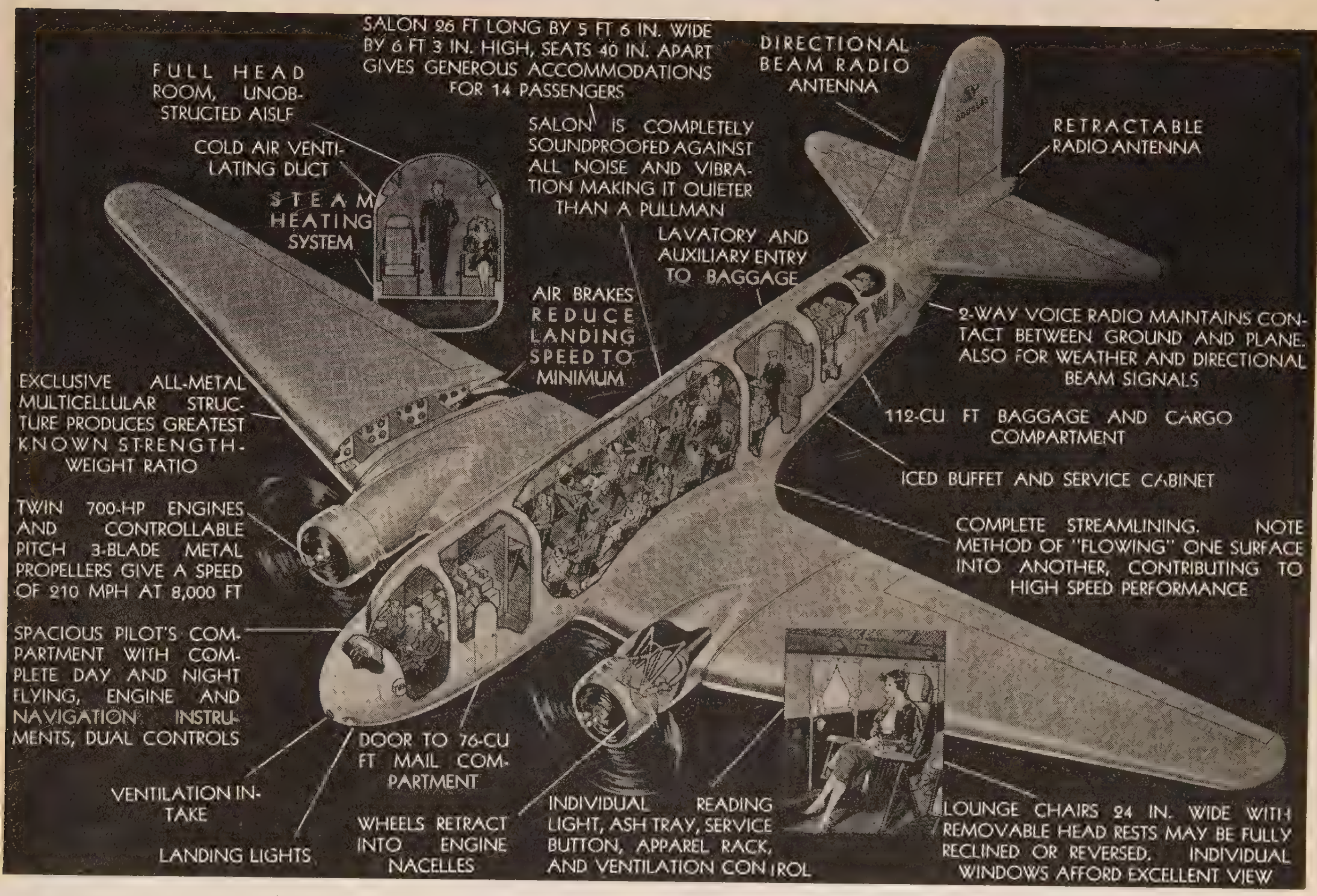
Fig. 1. If the turns of the inside winding are thinned out to half the density in that portion of the winding opposite the tap break, and if the turns so thinned out are crowded into the remainder of the winding, the diagrams in Fig. 4b show the result. This device results in about $^1/_4$ the maximum cross flux reactance and eddy current losses.

If instead of taking all of the taps from the center of the winding they are distributed at two points along the winding as in Fig. 4c, again the cross flux reactance and eddy current losses will be reduced to about $^1/_4$ of that resulting from the turn distribution in Fig. 4a. Now if the turns in that part of the winding opposite the 2 tapped out portions be thinned out, the cross flux reactance and eddy current losses will be reduced still further as shown by the diagrams in Fig. 4d.

The curves in Fig. 5 show the reactance of a transformer with 4 5-per cent taps cut from the center of one of the windings, compared with the same transformer with proper thinning of the turns of the winding opposite the tap irregularities.

This method has been in use for several years and has greatly simplified and improved the accuracy of the reactance and eddy current loss calculation of concentric winding transformers with irregularities in the windings. It also has been very helpful in indicating to the designer conditions of design that might result in high localized losses, and in enabling him to avoid such conditions.

Modern Transportation's Most Recent Contribution to Speed and Safety



THIS new transport plane, reported to be the fastest multimotor passenger carrier ever built, is made possible by modern engineering developments, among the most important of these being many of the recent developments in the electrical field. Electrical devices contribute much to the safety and comfort of flying. A fleet of 41 of these Douglas airliners are being placed in service on the lines of Transcontinental and Western Air, Inc.; these planes have a speed of 210 miles per hour at 8,000 ft altitude, and a landing speed of less than 60 miles per hour. Tests have proved that with only one of the 2 motors in operation the plane can take off, fly to an altitude of 9,000 ft and maintain a speed of almost 120 miles an hour. These planes incorporate, in addition to the many features noted on the diagram, Sperry hydraulic-pneumatic pilots for automatic flying. The automatic pilots keep the plane on a level and straight course in any kind of weather and leave the pilot free for other operations. Guests of the Institute's recent winter convention were afforded the opportunity of riding in 12-passenger planes of this same line, almost as modern as the one illustrated here.

News

Of Institute and Related Activities

Winter Convention Marked by Good Attendance

THE official registration of the Institute's 1934 winter convention recently held in New York, N. Y., Jan. 23–26, totaled 1,227 persons. This attendance was particularly gratifying to all who had worked to make the convention a success, as it is an appreciable increase over last year's registration. Also, there was a notable increase in out-of-town attendance. This, and other information, is revealed by a study of Tables I and II. The nominal registration fee charged all nonmembers except enrolled students and wives and children of members, and applied this year for the first time in recent winter conventions, apparently did not act to hold down the registration. Several innovations were introduced into this year's convention, as may be noted in the following paragraphs.

Table I—Registration at Recent Winter Conventions

1934	1,227	1928	1,475
1933	1,099	1927	1,317
1932	1,429	1926	1,423
1931	1,589	1925	1,445
1930	1,607	1924	1,738
1929	1,375	1923	1,200

Table II—Registration for 1933 and 1934 Winter Conventions

District	1933	1934
New York City and Foreign (3)	791	812
North Eastern (1)	130	179
Middle Eastern (2)	132	161
Great Lakes (5)	23	40
Canada (10)	14	16
South West (7)	2	11
Southern (4)	4	5
North Central (6)	2	2
Pacific (8)	0	1
North Western (9)	1	0
Total	1,099	1,227

Opening Session Included Presentation of Sprague Bust

The convention was opened on Tuesday, January 23, at 10 a.m., C. R. Jones, chairman of the winter convention committee presiding. Immediately following Mr. Jones's opening, J. B. Whitehead, president of the Institute, presented his message in which he stated that he considered the Institute's annual winter convention to be one of the most pleasurable of the Institute's activities. Continuing, he made an appeal for loyalty to the Institute by its members. President Whitehead then introduced Frank Hedley, president of the Interborough Rapid Transit Company, New York, N. Y., who delivered the presentation speech in connection with the gift to the Institute of a bust of Frank J. Sprague which was included as part of the convention's opening session.

Mr. Hedley, after commenting upon the three-quarter relief portrait bust of Doctor Sprague, whom he termed "The Father of Rapid Transit," introduced the sculptress, Florence M. Darnault, and congratulated her upon her artistic achievement in executing the Sprague portrait bust. Mr. Hedley then continued with a tribute to Doctor Sprague which was followed by the acceptance of the bust by President Whitehead. Appropriate remarks then were made by Doctor Sprague, which, together with Mr. Hedley's tribute, are reported in greater detail on succeeding pages of this issue. (A biographical sketch of Doctor Sprague is given in ELECTRICAL ENGINEERING for February 1932, p. 139–40, in connection with the award to him of honorary membership in the Institute.)

As the concluding event of the opening session, R. N. Conwell, chairman of the technical program committee announced the procedure for the technical sessions which were to follow.

Technical Sessions

The 10 technical sessions which were held during the winter convention are not included in this news report, as all of the technical papers which were discussed have already appeared in full in the issues of ELECTRICAL ENGINEERING for August, November, and December 1933, and January 1934. Discussions of these papers presented at the winter convention are scheduled for inclusion in future issues of ELECTRICAL ENGINEERING.

Judging from comments overheard during the convention the newly adopted practice of publishing all papers in ELECTRICAL ENGINEERING in advance of the meeting, thereby making unnecessary the distribution of pamphlet copies, met with widespread favor and added considerably to the value of the discussions of these papers during the convention sessions.

Education Session Held

In addition to the technical sessions of the convention, a session on education was held on Wednesday morning, as an open meeting of the committee on education and the committee on Student Branches. Both of these committees are under the chairmanship of L. A. Doggett, who presided at this session. Mr. Doggett presented a brief abstract of the current activities of these 2 committees. Following this a paper on "The University of Pittsburgh-Westinghouse Graduate Program" was presented by H. E. Dyche and R. E. Hellmund, following which J. W. Barker reviewed the activities of the Engineers' Council for Professional Development. Among the various points brought out in the discussion which followed was the suggestion that the committee work out some means whereby information of particular interest to students be brought to their attention regularly.

Women's Entertainment

The luncheon and bridge at the Engineering Women's Club, which has become a feature of the entertainment for women attending recent winter conventions was held this year on Wednesday, January 24, with about 40 present. In addition to the regular convention activities, including the dinner-dance at the Waldorf-Astoria, which are of particular interest to women, a trip exclusively for them was arranged to the Radio City broadcasting studios on Friday, January 26, where Walter Damrosch was broadcasting. About 60 women attended this trip. Mrs. H. R. Woodrow was chairman of the women's committee being assisted by Mrs. T. F. Barton, Mrs. C. R. Beardsley, Mrs. C. O. Bickelhaupt, Mrs. R. N. Conwell, Mrs. A. F. Dixon, Mrs. C. R. Jones, Mrs. E. B. Meyer, and Mrs. D. M. Simmons.

Buffet Dinner and Smoker

About 550 persons attended the annual smoker held on Tuesday, January 23. This attendance taxed to the limit the facilities for serving the excellent buffet dinner which the committee had arranged. Moving pictures were available in the auditorium during the latter part of the dinner period. Following the moving pictures a show was presented in the auditorium which brought forth many comments on the entertainment value and the mysteries of the performances.

R. A. McClenahen was the chairman of the smoker committee, assisted by E. S. Banghart, G. D. Edwards, W. H Farlinger, J. E. Goodale, H. C. Schlaijker, F. H. Stoppelman, E. E. Thrall, H. G. Wood, and J. E. McCormack.

Dinner-Dance and Buffet Supper Arranged

The combined dinner-dance and buffet supper was arranged for Thursday night, this combined event being held at the Waldorf-Astoria Hotel. Approximately 167 persons attended the dinner and dance, while approximately 168 took advantage of the opportunity of coming only for the dancing and the buffet supper served at midnight. About 129 attended both the dinner-dance and the buffet supper-dance, bringing the total attendance to 464. Preceding the dinner, a reception in honor of President Whitehead was held in the Basildon Room of the Waldorf-Astoria.

The flexibility of the plan arranged for this year proved attractive to many who otherwise would not have attended. The committee responsible for this successful affair consisted of George Sutherland, chairman, assisted by P. L. Alger, John Bassett, C. A. Butcher, C. M. Gilt, H. L. Huber, J. F. Kelly, R. F. Penman, C. S. Purnell, S. S. Reynolds, H. R. Searing. T. E. Shea, and D. M. Simmons.

Inspection Trips Concentrated on Friday

Another plan which differed from that of preceding winter conventions was the arranging of all regular inspection trips for the same day. Friday, January 26, was reserved for inspection trips at this convention, no technical sessions being held on that date. The visit to the studios of the National Broadcasting Company in the R.C.A. Building, attended by 107 persons, proved to be the most attractive. The trip which included the Hudson Avenue generating station, Brooklyn Edison Company's cafeteria, city subway rectifier substation, and Kings Brewery, attended by 56 persons, was next in order. Tied for third place were the trips to the Newark airport including a flight, and the trip to Electrical Research Products, Inc., where educational pictures were shown. Each of these 2 trips drew 37 registrants, while the motor bus trip through northern New Jersey where 3 radio stations were inspected was next in order with 34 registrants. The Roseland switching station of the Public Service Electric and Gas Company of New Jersey attracted 18 visitors, while smaller groups went to each of the other 6 prearranged trips. All together, 363 persons were registered for trips.

The inspection trips committee consisted of H. C. Otten, chairman, assisted by G. F. Fowler, Henry Kurz, S. A. Smith, Jr., H. B. Stoddard, E. R. Thomas, R. H. Twiss, and R. L. Webb.

Directors and Committees Meet

The meeting of the Institute's board of directors held on Monday, January 22, is reported elsewhere in the news section of this issue. Many committee meetings also were held during the convention; these were meetings of the committees on standards, power generation, communication, research, electrochemistry and electrometallurgy, transportation, power transmission and distribution, general power applications, technical program, automatic stations, protective devices, production and application of light, electrical machinery, and Sections. There also was a meeting of the sectional committee on electrical definitions, and an open meeting of the committees on education and student branches.

In charge of arrangements for the 1934 winter convention were the general committee and the convention executive committee. The general convention committee consisted of C. R. Jones, chairman, assisted by T. F. Barton, C. R. Beardsley, C. O. Bickelhaupt, R. N. Conwell, A. F. Dixon, E. B. Meyer, H. S. Osborne, and D. M. Simmons. The convention executive committee consisted of C. R. Beardsley, chairman, assisted by R. A. McClenahen, H. C. Otten, George Sutherland, and Mrs. H. R. Woodrow.

Principal Addresses Given in Connection With Frank J. Sprague Presentation

A BRONZE portrait bust of Frank J. Sprague (A'87, F'12, HM'32, and past-president) was presented to the A.I.E.E. as the outstanding feature of the opening session on January 23, of the Institute's recent winter convention held in New York, N. Y. The presentation was made by Frank Hedley, president of the Interborough Rapid Transit Company, on behalf of the Frank J. Sprague anniversary committee. The portrait bust was executed by Miss Florence Darnault.

The procedure followed at this presentation ceremony is outlined elsewhere in this issue as part of the general news report on the winter convention. Following is that part of the presentation speech made by Frank Hedley, president of the Interborough Rapid Transit Company, which applied to Mr. Sprague; following this Mr. Sprague's remarks are given.

Mr. Hedley's Tribute to Doctor Sprague

"Frank Julian Sprague, scientist, inventor, and engineer, and rightfully termed "father of electric traction," was born in Milford, Conn., on July 25, 1857. He attended the United States Naval Academy from 1874 to 1878. He represented the United States Navy at the Crystal Palace Exhibition in London in 1882. He resigned as ensign of the United States Navy in 1883. He became assistant to Thomas Edison with whom he was associated for one year. He then formed the Sprague Electric Railway and Motor Company. This was in 1884. That company received the contract for the Richmond, Va., Railways in 1887, followed by 110 other railways before merging with the Edison General Electric in 1890.

"In 1892 the Sprague Electric Elevator Company was formed for the development and promotion of electric elevators. The first battery was installed in the Postal Telegraph building in 1893. In 1895 he invented the "multiple-unit" system and placed his first installation on the South Side Elevated Railway in Chicago in 1897. In 1897 the Sprague Electric Company was formed and in 1902 this Company was absorbed by the General Electric Company.

"Mr. Sprague was a member of the commission for the electrification of Grand Central Terminal which lasted from 1903 to 1908. During that time, namely in 1906, he developed the automatic train control and organized the Sprague Safety Control and Signal Corporation. In 1927 he developed the dual elevator system and in 1929 new forms of electric signs.

Mr. Sprague has been awarded: The Gold Medal, Paris Electrical Exhibition, 1889; Elliot Cresson Medal, Franklin Institute, 1904; Grand Prize, St. Louis Exhibition, 1905; Edison Medal, A.I.E.E., 1910; and the Franklin Medal, Franklin Institute, 1921. He has received the honorary degrees of: doctor of engineering from Stevens Institute of Technology; doctor of science from Columbia University; and doctor of laws from the University of Pennsylvania. He is also an honorary member of: The A.I.E.E., 1932; Franklin Institute; and the Engineers' Club. He is past-president of: The A.I.E.E.; New York Electrical Society; American Institute of Consulting Engineers; and the Inventors Guild. During the late war he was a member of the United States Naval Consulting Board.

"As to his accomplishments, we who are engaged in transportation, properly take a particular pride in Mr. Sprague because of the major contributions which he has made to transportation. He, more than any other man, must be regarded as having brought electric transportation into practical being. He installed in Richmond, Virginia, in 1887 the first electric railway system of any size in the world. This is the parent of all modern trolley lines.

"The invention of the multiple-unit system of train operation a few years later marked the opening of another new epoch in transportation and an important one in that it permitted the make-up of a train of any length with all the characteristics of a single car. This system of combining a group of individual cars, each complete in all respects, and providing for operating all controllers simultaneously through a train line from a master switch on any car, offers the only possible method by which the exacting conditions, particularly of rapid transit in congested territory, may be met. Therefore, I say that in addition to being called the "father of the trolley line," Frank Sprague should be called also the "father of rapid transit."

"If I were called upon to name the most powerful influence contributed by Frank Sprague to the railway industry, I think I should say it was his pioneering vision, supplemented by his fighting spirit. His vision

has been translated into accomplishment to such an extent that transportation, while considered by us a dynamic industry, has become very commonplace in the public mind. The passenger is seldom conscious of the almost miraculous devices employed in carrying him back and forth through the city and country, under rivers and over mountains, with a remarkable degree of safety and comfort. It is only on occasions such as this that an opportunity is afforded to remind people of what is going on around them that is so necessary to their daily lives and to which they naturally give no thought.

"The traveling public using our rapid transit lines here in New York City, with which most of you are familiar, owe, and always will owe, a tremendous debt to Frank Sprague for his remarkable inventive genius, which has given them a type of service which never could have been rendered without the use of his ingenious devices; and, of course, this is equally true with respect to rapid transit travelers wherever such facilities exist throughout the world.

"In closing, I give you the following quotation written by the editor of one of our leading technical magazines: 'Inventors there have been whose talents lay so wholly in invention and so little in life, that they lacked either the driving force to get their ideas before the public, or the ability to make friends or at least believers who would attend to such details for them. But once in a while there appears a man whose grasp on business affairs is equal to his superlative inventive ability—an inventor, a fighter, a pusher—one who is not content to produce what is new and better, but who will fight to the last gasp and the last penny to force an uninterested and reluctant world to adopt what he has to give. Such a man is Frank J. Sprague, who more than any other one man must be recognized as having brought electric transportation into being.' "

Remarks of Doctor Sprague

Following acceptance of the bronze portrait bust of Doctor Sprague by President Whitehead, Doctor Sprague remarked as follows:

"It is a curious coincidence that this year of 1934 marks not only the end of a half century since the holding of the first Electrical Exhibition at Philadelphia and the founding of the American Institute of Electrical Engineers, but it is also the Jubilee of my independent entrance into the electric power field, although while a cadet midshipman I had for some years been concerned with electrical matters.

"A kindly Providence has, in spite of the steady march of the calendar, permitted me the privilege of witnessing, and also contributing something to, the development of the modern electric age, which, while largely based upon the experiments and discoveries of Faraday and Henry, received its major impulse, both in this country and abroad, on the installation of the first general electrical supply station in 1882 under the courageous leadership and responsibility of Mr. Edison.

"Although briefly associated with him as a mathematical and technical assistant in central station work, I continued strongly imbued with the conviction that the use of electricity for industrial power and traction would play a major part in its function as a universal servant. An early resignation has been followed during many more or less controversial years in fostering that belief by practical work, and a year and a half ago, when I finished my three-quarter century stretch, many colleagues, and friends were good enough to note that event here in a unique birthday party, attended by many evidences of highly prized character.

"Now, under the auspices of the same committee, and with the coöperation of Miss Darnault, the sculptor, whose talent and patience in handling a somewhat difficult subject I deeply appreciate, a portrait bust has been tendered the Institute as a token of recognition of work in specific fields. In accepting this, Dr. Whitehead, you and the great society over which you now preside, and which it has been my privilege to serve, have done me signal honor in giving it a home among its immortals.

"I find difficulty in expressing my appreciation in being thus transposed from the record of the printed page and the photograph into a metallic replica exposed to present and future critics, but I would not be human if I, and those who are my kin did not feel a deep inward satisfaction.

"May I also record a debt of indirect association with a great university? Under the leadership of Henry Rowland, John Hopkins established preëminence in the scientific world. Incidentally, he made the first report on my embrionic railway developments. His successors, Doctor Duncan and Doctor Hutchinson, became my associates and coöperated in building the first large electric locomotive. Now you, Doctor Whitehead, who as dean of the engineering councils, have for many years happily carried the burden of maintaining the Rowland standard, have again placed me under a happy obligation.

"As I look back over an active past I often ask myself what has been the guiding impulse, and what is the heritage I most wish to leave. As to the first, there has been an impelling urge for creation, in which I have tried to be guided by the rigid tenets of a naval training and the high ethical standards of our beloved profession; and second, that as it is better to give than to receive, to help rather than hinder, and to do rather than hesitate, it is one's highest privilege and most lasting satisfaction to contribute in some effective fashion to the general good of humanity. May I venture the hope that, as evidenced by the generous remarks of Doctor Whitehead and Mr. Hedley, such will remain the verdict of electrical history.

"It has never been my good fortune to devote myself to the joys of pure research, of the kind that crowns the work of many brilliant and devoted scientists, but rather to combine invention and work for current needs. But whatever the sources of endeavor the marriage of ideal conception and discovery with practical application is essential to insure progress in our work-a-day civilization.

"As to the future, I will not venture into prophecies additional to those I have often made. On the one hand the astronomer and mathematician, with the aid of the physicist, seeks solution of the beginning, extent and future of an incredibly vast celestial universe, and on the other, the masters of science, largely with the aid of electrical equipment, strive to break through the infinitesimal but mighty barriers which protect the structure of the atom, and even to seek the source of life itself. Whatever, and however interesting, the results, I question the optimistic predictions of unlimited and economic sources of power from the breakdown of the atom's structure.

"What to me is of present transcendent

Portrait bust of Frank J. Sprague presented to the Institute on behalf of the Frank J. Sprague anniversary committee by Frank Hedley (right) during the opening session of the recent winter convention. Dr. Sprague (left) in his remarks following the presentation expressed his great appreciation of this tribute

importance is to make the fullest use of what we have at hand. Naturally, I look to a greatly enlarged use of electricity in the railroad field, partly with the help of the Government funds, as some time ago I urged as a fully warranted activity in the current public works program.

"Time does not permit me to discuss the many new projects, here and abroad, but I would refer to the recent reports of the British Commission, the provision for extension of the electrification of the Pennsylvania Railroad, and the ambitious proposal by Mr. McDonald detailed at the last meeting of our sister-society, that of the Civil Engineers.

"While I again express my heartfelt thanks to the Institute, to Miss Darnault and to the committee, may I register the universal feeling of relief on the recovering from a serious illness, of our former president, Dr. Gano Dunn, and also express the great grief with which old friends and associates have learned of the recent sudden death of Mr. William B. Potter, a gifted and active pioneer and upbuilder in the electric railway field."

Future AIEE Meetings

North Eastern District meeting,
Worcester, Mass., May 16–18, 1934

Summer convention,
Hot Springs, Va., June 25–29, 1934

Pacific Coast convention,
Salt Lake City, Utah, Sept., 1934

Edison Medal for 1933 Presented to Doctor Kennelly

With ceremony simple but fitting to the occasion, the Edison Medal, highest award of the A.I.E.E., for 1933 was presented to Dr. Arthur Edwin Kennelly for "meritorious achievements in electrical science, electrical engineering, and the electrical arts as exemplified by his contributions to the theory of electrical transmission and to the development of international electrical standards." Doctor Kennelly is professor emeritus of electrical engineering, Harvard University and Massachusetts Institute of Technology; he is an honorary member and past-president of the A.I.E.E. Doctor J. B. Whitehead, president of the A.I.E.E., presented the medal, together with a certificate bearing the foregoing citation, at a special session of the Institute's recent winter convention, held during the evening of January 24, 1934. After brief introductory remarks, President Whitehead called upon Mr. C. E. Stephens, chairman of the Edison Medal committee, to outline briefly the history of the medal; Mr. Stephens' remarks follow.

History of Edison Medal Outlined by C. E. Stephens

"The Edison Medal was founded 20 years ago (February 11, 1904) by an organization of associates and friends of Thomas A. Edison who desired to commemorate the achievements of a quarter of a century in the art of electric lighting with which Edison had been so prominently identified.

"It was decided that the most effective means of accomplishing this object was by the establishment of a gold medal which could serve 'as an honorable incentive to scientists, engineers, and artisans to maintain by their works the high standard of accomplishment' which had been set by Edison. The American Institute of Electrical Engineers was invited to undertake the responsibility of making the awards. The Institute accepted, and organized the Edison Medal committee, or board of award, composed of 24 members.

"Three of these members are appointed each year by the president of the Institute to serve for a term of 5 years each; 3 are elected each year by the Board of Directors from its own membership to serve for a term of 2 years each; the other 3 members are *ex-officio*—the president, the national treasurer, and the national secretary of the Institute.

"The by-laws of the committee provide for making one award each year, and the deed of gift specifies that the award shall be made to some one resident in the United States or Canada, for meritorious achievement in electrical science, electrical engineering, or the electrical arts.

"The medal was designed by James Earle Fraser, and carries on the obverse the portrait of Thomas A. Edison and on the reverse an allegorical conception of the genius of electricity crowned by fame.

"Previous awards have been made as follows:

1909 Elihu Thomson. For meritorious achievement in electrical science, engineering and arts, as exemplified in his contributions thereto during the past 30 years.

1910 Frank J. Sprague. For meritorious achievement in electrical science, engineering and arts, as exemplified in his contributions thereto.

1911 George Westinghouse. For meritorious achievement in connection with the development of the alternating-current system for light and power.

1912 William Stanley. For meritorious achievement in invention and development of alternating-current systems and apparatus.

1913 Charles F. Brush. For meritorious achievement in the invention and development of the series arc lighting system.

1914 Alexander Graham Bell. For meritorious achievement in the invention of the telephone.

1916 Nikola Tesla. For meritorious achievement in his early original work in polyphase and high-frequency electrical currents.

1917 John J. Carty. For his work in the science and art of telephone engineering.

1918 Benjamin G. Lamme. For invention and development of electrical machinery.

1919 W. L. R. Emmet. For inventions and developments of electrical apparatus and prime movers.

1920 Michael I. Pupin. For his work in mathematical physics and its application to the electrical transmission of intelligence.

1921 Cummings C. Chesney. For early developments in alternating-current transmission.

1922 Robert Andrews Millikan. For his experimental work in electrical science.

1923 John W. Lieb. For the development and operation of electric central stations for illumination and power.

1924 John W. Howell. For his contributions toward the development of the incandescent lamp.

1925 Harris J. Ryan. For his contributions to the science and the art of high-tension transmission of power.

1927 William D. Coolidge. For his contributions to the incandescent electric lighting and the X ray arts.

1928 Frank B. Jewett. For his contributions to the art of electrical communication.

1929 Charles F. Scott. For his contributions to the science and art of polyphase transmission of electrical energy.

1930 Frank Conrad. For his contributions to radio broadcasting and short wave radio transmission.

1931 E. W. Rice, Jr. For his contributions to the development of electrical systems and apparatus and his encouragement of scientific research in industry.

1932 Bancroft Gherardi. For his contributions to the art of telephone engineering and the development of electrical communication.

"I read these names with reverence; the achievements of the recipients are as varied as the personalities of the men themselves. Their names stand for progress in generation of electric power, in its transmission, in its utilization and in its use for transmission of intelligence—in fact, these names have figured prominently in every development of the use of electricity which has made our lives more livable. And tonight we are gathered here to add to that great honor roll the name of Dr. Arthur E. Kennelly."

Kennelly Career Outlined by Dr. Clayton H. Sharp

Following Mr. Stephens' brief history of the Edison Medal Dr. Sharp, longtime member of the Institute (A'02, F'12) outlined Dr. Kennelly's career:

"The body of science and technology on which electrical engineering is based is the work of many men of diverse talents. There have been experimental physicists, theoretical physicists, mathematicians, inventors, and finally engineers who, taking the mass of experimental facts, of substantiated theory and of successful inventions, have leavened it with their own practical knowledge, experience, and resourcefulness and have produced the huge and useful structure which is the electrical industry of today. Most of the workers in this science have been capable of classification in one or more of these groups. However certain ones, by the versatility of their genius, defy classification. They take a high place in the hierarchy of pure scientists. As mathematicians they are not plodders, they are originators. Withall, they are, in the highest sense of the term, practical men; inventors and engineers. The chief of this group was Lord Kelvin. It is to this group

that Doctor Arthur Edwin Kennelly belongs.

"Like another illustrious member of the group, Professor Elihu Thomson, Doctor Kennelly is of British parentage. He was born in India and educated in England, Scotland, France, and Belgium. His first position was that of assistant secretary of the Society of Telegraph Engineers of London, now the Institution of Electrical Engineers. In 1876 he joined the Eastern Telegraph Company, thus entering into the most highly developed electrical field of that time. He was promoted steadily until in 1886 he became senior ship electrician on submarine cables, a position which made severe demands on the technical knowledge and resourcefulness of the occupant. It is reasonable to infer that his familiarity so gained with the theory and practice of the transmission of signals over long lines having distributed capacity formed the basis for his future work in the field of telephony and in the mathematical treatment of the phenomena of transmission lines.

Became Associated With Edison in 1887

"He came to America in 1887 and became the principal electrical assistant to Mr. Thomas A. Edison, which position he held until 1894. These years in a hard and intensely practical school could not have been other than instructive and stimulating to a young engineer. In 1893 he was, in addition, consulting electrician to the Edison General Electric Company now the General Electric Company, which is good enough evidence of the success of his work with Mr. Edison.

"In 1902 he was appointed professor of electrical engineering at Harvard University and occupied that chair until his retirement as professor emeritus in 1930. During the years from 1913 to 1924 he also was professor of electrical engineering at Massachusetts Institute of Technology and now is professor emeritus of that institution also. During some years of his active service at M.I.T. he was director of electrical engineering research and chairman of the faculty.

"With all these duties and responsibilities Doctor Kennelly nevertheless has found time and energy to engage in many outside activities. He has served 2 terms as President of the A.I.E.E. (1898–1900). He was president of the Illuminating Engineering Society during the early days of that organization when his guidance was particularly valuable. He has been president of the Institute of Radio Engineers, of the Metric Association, and of the Union Radio Scientifique Internationale. He is honorary secretary of the United States National Committee of the International Electrotechnical Commission.

International Efforts

"In the international field his services have been of unusual distinction. He was a United States delegate to The Electrical Congresses of 1900, of 1904 where he carried out the onerous duties of general secretary, and of 1932; also to international radio conferences in Paris in 1921 and in Washington in 1927 where international allocations of radio transmission frequencies were made. He is a member of the International Committee on Weights and Measures, the last meeting of which at Sevres in 1933 Doctor Kennelly attended. During the year 1921–22 he represented 7 coöperating American universities as first exchange professor in engineering and applied science at several French universities. He has published many books and is the author of more than 350 papers many of which were presented before scientific organizations at home and abroad. Without stint he has given of his time in committee work in accomplishments for which he has neither desired not received personal credit. At the present time he is chairman of the Committee on Electrical Definitions which already has accomplished an important work.

"Doctor Kennelly joined the A.I.E.E. as an Associate in 1888. In 1894 he had already became a manager, having among his colleagues in that office Pupin, Steinmetz, Ryan, and Carty. He was also chairman of the only technical standing committee of the Institute, namely, the committee on units and standards. The committee was wrestling with the question of the names of the magnetic units. Forty years later we find Doctor Kennelly chairman of the advisory committee of the International Electrotechnical Commission which is laboring on the same subject. Doctor Kennelly has been at the forefront of all the discussions of all the intervening years. At the Paris Congress of 1901 it was Kennelly who delivered the vote of the United States. We expect that he will succeed in his task of getting complete international accord, for in power of reasoning and persuasion he is unexcelled. This is only one instance. For 45 years the TRANSACTIONS of the Institute have been enriched by his contributions of papers and discussions.

Classic A.I.E.E. Contribution in 1893

"One of these contributions, which is now a classic, demands further consideration even in as brief a review as can be made in the time allotted for this discussion. In April 1893 (TRANS., v. 10, p. 175) Doctor Kennelly presented a paper under the title 'Impedance' in which he gave the first application ever to be made of complex quantities to technology, and to the extension of Ohm's law to alternating circuits. In the paper he first showed that in a circuit containing resistance and inductance, the impedance is given by the hypothenuse of a right triangle, the other sides of which are the resistance and a quantity which he called the inductance-speed, namely the inductance multiplied by 2π times the frequency. He said: 'The impedance is therefore the geometrical or vector sum of the resistance and inductance-speed, when these are plotted on two rectangular axes. Calling this impedance i, Ohm's law gives

$$c = \frac{e}{i} \qquad e = ic \qquad i = \frac{e}{c}$$

corresponding to the usual formulas for continuous currents.'

"The paper went on to show how the impedance of reactors in series is given by the vector sum of their individual impedances; how the impedance triangle of a resistance in series with a condenser is drawn, taking the reciprocal of the capacity-speed of the condenser as the vertical side of the triangle and turning it downward; how problems of resistance and reactances in multiple may be solved by vector methods.

"Finally Doctor Kennelly enunciated the following general law. Any combination of resistances, non-ferric inductances, and capacities, carrying harmonically alternating currents, may be treated by the rules of unvarying currents, if the inductances are considered as resistances of the form $pl\sqrt{-1}$, and the capacities as resistances of the form $-\frac{1}{kp}\sqrt{-1}$, the algebraic operations being then performed according to the laws controlling complex quantities.

Times Wide World Photo

Dr. J. B. Whitehead (left) president of the A.I.E.E. presenting the 1933 Edison Medal to Dr. Arthur E. Kennelly at the special ceremony on January 24, 1934, held during the Institute's recent winter convention in New York

"How completely novel the method and the ideas set forth in the paper were is indicated by the fact that the members called upon to discuss it (and they included some who were already famous in the profession, at least one of whom later became an Edison medallist) expressed their appreciation of it, but declined to make further comment on the ground that they had not 'had time to digest it.' Yet, today, how simple and commonplace it all seems!

Supported by Steinmetz

"However, Doctor Steinmetz, who had not been present at the meeting, sent in after adjournment a written discussion from which it is seen that his keen mind had instantly grasped the full significance of Doctor Kennelly's disclosure. He wrote, after quoting the (Kennelly) rule and emphasizing its significance:

" 'It is well known that the points of a plane can be represented by complex quantities in their rectangular representation $a + bj$, or their polar representation r (cos $\phi + j$ sin ϕ), and use has been made hereof repeatedly in the mathematical treatment of vector quantities. It is, however, the first instance here, so far as I know, that attention is drawn by Mr. Kennelly to the correspondence between the electrical term impedance and the complex numbers.'

" 'The importance hereof lies in the following: The analysis of the complex plane is very well worked out, hence by reducing the electrical problems to the analysis of complex quantities they are brought within the scope of a known and well understood science.'

"Doctor Steinmetz's subsequent development and use of the method in his many published works have been largely responsible for the familiarity which we have with it today; so much so that the credit for the original idea is sometimes given to him. It is interesting on this occasion to note that this whole matter was one of the results of the work which Doctor Kennelly did while associated with Mr. Edison.

"In April 1895 Doctor Kennelly, in collaboration with Professor Houston, presented the first of his many papers employing complex angles in dealing with transmission line problems.

Kennelly–Heaviside Layer

"The thing for which Doctor Kennelly is best known is undoubtedly his explanation of the mechanism of the transmission of radio waves. In the beginnings of radio telegraphy it was supposed, most reasonably, that radio transmission to any great distance was practically hopeless, both on account of the curvature of the earth's surface and because with the field strength varying inversely as the square of the distance, the energy would be attenuated very rapidly. Marconi's audacity in putting this idea to the test in his famous Cornwall to Newfoundland experiment, proved that this was not so. Evidently some unknown factor intervened to change the conditions. To explain this it might be supposed that there exists high up in the earth's atmosphere, a conducting region or layer by which the radio waves are deflected and turned back toward the earth, so that the curvature is overcome and the energy spread restricted to two dimensions. Thus the attenuation of signals would vary with the first power of the distance instead of the square. Doctor Kennelly not only did this but he went much further.

"His publication of the matter in the number of the *Electrical World and Engineer* for March 15, 1902, had the significant title On the Elevation of the Electrically-Conducting Strata of the Earth's Atmosphere. In this article he did not assume the existence of purely speculative conducting strata but, basing his calculations on data of J. J. Thomson's, he showed that electrically conducting strata must exist because of the rarefaction of the atmosphere, at a height of the order of 50 miles, with a conductivity several times as great as that of sea water. The presence of such strata being thus assured from independent consideration, the explanation of long-distance radio transmission followed at once and was given with precision and clearness and for the first time.

"Doctor Kennelly is noted for his accuracy of statement. If he cites a numerical value which is not exact even unto the third and fourth generation of decimals, he calls it an approximate value. He never leaves the reader in doubt as to what units he is employing. He has introduced a simple system of prefixes: 'ab' for the absolute magnetic system and 'stat' for the absolute electrostatic system.

Efforts Toward Practical System of Units

"He has been endeavoring for years, chiefly through the International Electrotechnical Commission, to get an agreement on an absolute practical system of units which should include the mechanical as well as the electrical units. The prospects for success have become much brighter during the past year.

"In conferences and in committee work his urge is always to get something tangible done, something agreed to. An imperfect agreement is better than no agreement, for at least it records progress made and can later be amended. He never attempts to force his own views on his colleagues. Stubbornness and pride of opinion or of parentage are foreign to his nature. He sees his adversary's point of view as well as his own, and is always fair, judicial, and tolerant. The combination of these characteristics with a complete mastery of his subject accounts for the large measure of success which his work in these directions has achieved.

World-Wide Recognition

"We, who have been his associates for many years, have known the modesty of his deportment, the geniality of his personality, the transparent honesty of his nature and the loyalty of his friendship. We have, perhaps, been too close to him to realize readily what his stature is among his contemporaries. The many scientists and engineers in foreign lands who know him personally and through his writings have, at their distance, been in a more favorable position. Thus, while he is an Honorary Member of this Institute, he is an Honorary Member of the Institution of Electrical Engineers of London, of the Societe Francaise des Electricians, of the Elektrotechnischer Verein and of the Institute of Electrical Engineers of Japan. He is a Corresponding Member of the British Association for the Advancement of Science and a Fellow of the Royal Astronomical Society.

"His affiliations at home are not confined to engineering organizations. He is a Member of the National Academy of Sciences, of the American Philosophical Society, of the American Mathematical Society, of the American Physical Society, and of the American Association for the Advancement of Science. He is a Fellow of the American Academy of Arts and Sciences.

Early Recognition

"This is not the first occasion on which Doctor Kennelly has received an award. As a young man, in 1887, he received the Institution Premium from the Institution of Electrical Engineers, and in 1889 he received the Fahie Premium from the same body. The Franklin Institute of Philadelphia granted him the Longstreth silver medal in 1916 and the Howard Potts gold medal in 1917. He was the recipient of the Volta medal in 1927 and the gold medal of the Institute of Radio Engineers in 1932. The French Government has conferred on him the Cross of the Legion of Honor.

"In the list of distinguished engineers on whom the American Institute of Electrical Engineers has conferred the Edison Medal, the highest honor which it can bestow, none has been more worthy than Doctor Arthur Edwin Kennelly."

Dr. Kennelly Extols Edison in Response to Presentation

Immediately following Dr. Sharp's biographical discourse President Whitehead read the citation and presented medal and certificate to Dr. Kennelly who, in responding stated to Dr. Whitehead that ". . It seemed to me that behind your welcoming hand I could imagine the hand of Mr. Edison," Dr. Kennelly then spoke at length upon the life and works of his onetime associate, Thomas A. Edison, in whose honor the medal is named:

"I think it is fitting that upon this occasion when the twenty-third Edison Medal is awarded, and 2 years after the death of our great chief, Edison, himself, that we should pause and take stock . . . .; we should see what they have meant to us and what he has meant to us. Mr. Edison was a pioneer electrical generation and distribution engineer, a pioneer illuminating engineer, and a pioneer acoustical engineer. I have taken the liberty of presenting to you here, through the kindness of the Edison Works and Mr. Denning, an early model of the Edison Phonograph, about the vintage of 1878, the tin foil phonograph from which he made this great discovery. He was the first acoustical engineer to record and reproduce sound, music, and speech . . . . (Dr. Kennelly then spoke into the relic which subsequently reproduced his statements loudly enough for most of the 800 persons present to hear; motive power furnished by Mr. Denning.)

Mr. Edison not only discovered the phonograph but he also produced the carbon button transmitter . . . . which made the Bell Telephone . . . . practical for service in everyday life.

"He also was the first to produce a loud speaker . . . . (exhibits device) . . . . a so-called chalk telephone receiver or electric motorgraph, in which a little moistened chalk cylinder is mounted in such a way that an electric contact connected mechanically with the vibrating diaphragm can be allowed to press softly upon the cylinder of chalk. When a very feeble alternating speech or voice current is passed through the contact the electrolytic effect of the current alters the friction between the stationary vibratory points and the slowly moving cylinder. The vigor and power of the sound that that instrument produces is astonishing. Of course, it had to be rotated either by moto or by hand and Mr. Edison had contemplated in the later part of his life to make this instrument practical for loud speaking, but I think he never carried his development . . . . very far. I merely wanted to show how much we owe Mr. Edison as an acoustical engineer.

"Then we all know how much we owe to Mr. Edison in regard to electric lighting and illuminating engineering. . . . The fact that we enjoy all these products of his hard work and development is lost upon us by familiarity. . . . . It was not merely his genius as an inventor, but his wonderful tenacity of purpose, his wonderful capability of holding on to a problem, his faith in the success of a problem which made the electric age possible to us.

"The wonderful improvements that have taken place since Mr. Edison's time are shown in many ways, but a striking way is the fact that in the days when I first came to work for him, electric motors of the ordinary constant-potential type had to be watched; you couldn't let them work long out of your sight. If the load on the motor varied considerably, they sparked at the brushes. Today we know that engineers take electric motors and seal them up inside refrigerators and don't allow you to look at them or touch them for a year or more. . . . So I hope . . . . that this medal may be a reminder to us all of how much we owe to the great man in whose honor this medal was founded.

"The future of electricity is beyond our perception, beyond our estimate. It is advancing with great rapidity. The electric switch is the great device by which all our daily tasks are made so much easier than they used to be. In the days of Ancient Greece and Rome the work . . . . was rendered lighter through the agency of slaves, captured in war, from whom you could get perhaps (the equivalent of) 20 watts each as a regular performance. Of course, they were not expected to be highly enthusiastic over his work, but you could count them about 20 watts apiece. But the average power that is available for every man, woman, and child in the United States is, as you know, about 60 watts per head, day and night . . the equivalent of . . 3 electric slaves potentially at work at the bidding of each individual. Formerly, in the days of Greece and Rome, you had to know how to handle your slaves in order to make them carry on with any degree of reasonable achievement. If you were too severe, if you cut their heads off, the rest remained rather sour and you couldn't do very much with them. Sullen slaves always indicated a hard taskmaster, but a man who could make his slaves fairly enthusiastic and stir them up to achievement was a man who was successful in that period in carrying on his work. We don't have to consider our electrical slaves, our motors and our lamps, and so forth. All we have to do is to turn the switch when we are finished with them. All this achievement, all this prospect and possibility, lying before us and before our successors, is largely due to the man in whose honor this medal has been founded."

A.I.E.E. Directors Meet During Winter Convention

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute Headquarters, New York, N. Y., on January 22, 1934.

There were present: *President*—John B. Whitehead, Baltimore, Md. *Past-president*—H. P. Charlesworth, New York, N. Y.; *Vice-presidents*—R. B. Bonney, Colo.; A. H. Hull, Toronto, Ont.; J. Allen Johnson, Buffalo, N. Y.; E. B. Meyer, Newark, N. J.; R. W. Sorensen, Pasadena, Calif.; and A. M. Wilson, Cincinnati, Ohio. *Directors*—L. W. Chubb, East Pittsburgh, Pa.; A. B. Cooper, Toronto, Ont.; A. E. Knowlton, New York, N. Y.; G. A. Kositzky, Cleveland, Ohio; Everett S. Lee, Schenectady, N. Y.; A. H. Lovell, Ann Arbor, Mich.; L. W. W. Morrow, New York, N. Y.; A. C. Stevens, Schenectady, N. Y.; R. H Tapscott, New York, N. Y.; and H. R. Woodrow, Brooklyn, N. Y. *National treasurer*—W. I. Slichter, New York, N. Y. *National secretary*—H. H. Henline, New York, N. Y.

Minutes were approved of the board of directors' meeting held October 20, 1933, and of the executive committee's meeting of December 8, 1933.

The board approved the finance committee's report of monthly disbursements amounting to $13,873.96 in December and $19,625.36 in January.

Authorization was given for a joint student activities conference of Districts Nos. 8 and 9 during the Pacific Coast convention, Salt Lake City, in September 1934.

Reports were approved of meetings of the board of examiners held December 20, 1933, and January 17, 1934. Upon the recommendation of the board of examiners, the following actions were taken upon pending applications: 5 applicants were transferred to the grade of Fellow; 36 applicants were transferred to the grade of Member; 11 applicants were elected to the grade of Member and 89 were elected to the grade of Associate as of February 1, 1934; 192 Students were enrolled.

A resolution was adopted to the effect that the 1934 annual meeting of the Institute will be held at Hot Springs, Va., on Monday, June 25.

Amendments to the by-laws were adopted, containing the new prices for Institute technical publications made necessary by the recent changes in publication policy. These prices have been announced in ELECTRICAL ENGINEERING.

The committee on Iwadare Foundation reported that it had arranged for Dr. C. E. Skinner to give a series of lectures in Japan next spring, under the Iwadare Foundation.

C. A. Adams and C. E. Skinner were reappointed as the Institute's representatives upon the council of the American Association for the Advancement of Science for the year 1934.

Upon recommendation of the standards committee, the board approved the reorganization of the Sectional Committee on Scientific and Engineering Symbols and Abbreviations, as follows:

1. The continuation of the present Sectional Committee *Z*10, but that the committee have charge only of "standardization of symbols and signs for equations and formulas," under the joint sponsorship of the same 5 organizations now sponsors.
2. The organization of a new Sectional Committee under the joint sponsorship of A.I.E.E., A.S.M.E., and A.S.C.E., to have charge of "the standardization of graphical symbols and of abbreviations."
3. Inclusion of the work now covered by Sectional Committee *C*10, electrical equipment of buildings, in the scope of the new Sectional Committee.
4. The inclusion of the work of subcommittee 6 of Sectional Committee *Z*14 on drawings and drafting room practice in the scope of the new Sectional Committee.

The annual report of the president of the U.S. national committee of the International Commission on Illumination was received, and the question of its publication in ELECTRICAL ENGINEERING was referred to the publication committee.

The board voted that in future information regarding the Institute budget shall be published in ELECTRICAL ENGINEERING.

Upon recommendation of the committee on research, in view of the retrenchment policy of the Federal Government, the board adopted a resolution calling attention to the importance of adequately maintaining the technical standardizing and research activities of the Bureau of Standards in the electrical field. (This resolution is published elsewhere in this issue.)

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

Student Convention at M.I.T. Successful

The first New England student convention including all the A.I.E.E. Student Branches in New England was held at Cambridge, Mass., on December 9, 1933, under the sponsorship of the Massachusetts Institute of Technology. The afternoon session opened the program, an address of welcome being given by Dr. Karl T. Compton (F'31) president of M.I.T., followed by the student papers. These were "Cable Testing" by Mr. Smith of Harvard, "Electrical Prospecting" by Mr. Fink of M.I.T., and "The Electrical Brain" by Mr. Krim. A talk on "Electrostatic Generation of High Voltages for Atomic Disintegration" was given by Dr. van de Graaff. Approximately 200 students and faculty members attended this meeting, which was followed by an inspection of the electrical laboratory.

The convention included a dinner meeting in the evening, at which there were 100 present to hear Dr. D. C. Jackson (A'87, F'12) compliment the students on the success of their convention, and to hear Prof. W. H. Timbie (A'10, F'24) tell of the interest and belief of the national organization in the students. Following these talks a lecture and demonstration on the sodium

vapor light were given by C. A. B. Halvorson (M'22) of the General Electric Company, Lynn, Mass.

Chairmen's Meeting Held

Following the afternoon session of the convention, a meeting of the Branch chairmen were held. Present were:

R. F. Wilson	Yale University
Ralph Dixon	Brown University
Amos E. Kent	Rhode Island State College
Stephen Smith	Harvard University
R. M. Dougherty	University of Maine
Henry Backenstoss	Massachusetts Institute of Technology

At this meeting it was agreed that the session just concluded had been very successful and was worthy of continuation. Means of promoting the next New England student convention were discussed, and suggestions were made for organizing and conducting future meetings. It was felt that the time of the year at which the meeting was held was suitable. Regarding the general lack of student papers, all agreed that this would be remedied in future years, when the students would be aware of the meeting far in advance. It was suggested that the meeting place be shifted among the various schools; Harvard spoke for the 1934 meeting, and Brown for the 1935 meeting.

Counselor's Conference

A meeting of the Student counselors also was held following the main afternoon session. Present were:

William Anderson	Rhode Island State College
W. B. Hall	Yale University
F. N. Tompkins	Brown University
R. G. Porter	Northeastern University
W. H. Timbie	Massachusetts Institute of Technology

The counselors were enthusiastic concerning the large attendance of students to the convention and the high standard of the papers, as well as the excellent manner in which they were delivered. The problem of membership of Student Branches was discussed, the opinion being expressed that the local membership was undesirable, but necessary at the present time. Methods of encouraging the students to join the national organization rather than the local organization were presented, and it was hoped that some progress on the solution of the problem of student membership could be made during the coming year.

Demonstration of Music in Auditory Perspective

A fine demonstration of transmission and reproduction of speech and music in auditory perspective was given during the Institute's recent winter convention on the evening of Wednesday, January 24, immediately following the Edison Medal presentation ceremony. Dr. Harvey Fletcher of the Bell Telephone Laboratories, Inc., conducted this demonstration and interposed appropriate remarks so as to give to the audience, many members of which were not technically minded, some appreciation of what was taking place, and what the future possibilites were of these new developments in the transmission and reproduction of sound. As the technical features of the equipment had been discussed in considerable detail during the technical session on communication held during Wednesday afternoon, and as these papers were published in full in the January 1934 issue of Electrical Engineering, no discussion of the technical features is included in this news report.

Doctor Fletcher explained that in addition to several features necessary for the satisfactory reproduction of music and which previously have been available, a new feature is now added which makes possible the control of the apparent "direction" of the sound reproduced. Previous progress in reproduction has been concerned with improving the quality, in the sense of reproducing with greater fidelity all the tones and overtones present in the original and reproducing them in their correct proportion, and with increasing the range of volume, or intensity. The new feature demonstrated by Doctor Fletcher enables the addition to the previously available qualities, of the illusion of localization of sounds from different sources.

This method of reproduction, termed "auditory perspective," makes it possible for the first time to transmit and reproduce electrically the music of a symphony orchestra so that the audience is unable to detect except by sight that the orchestra is not present. The feeling is produced in the audience of being able to detect, or localize, the different stage positions from which the various sounds come.

In demonstrating the equipment, Doctor Fletcher not only showed the audience the æsthetic effects which were available only by the reproduction of music by this method, but also performed many "tricks" which mystified the audience. Sounds of different kinds were made to move about the stage in a weird and often amusing fashion. Other demonstrations included the varying of the sound gradually from the lowest frequency audible to the human ear to the highest, and the control of the intensity of sound over a great range. Particularly at the lower frequencies, parts of the auditorium, such as windows, were caused to vibrate and produce considerable noise themselves. As the frequency was varied, these points of vibration traveled to different parts of the auditorium, producing a very ghostlike effect and forcefully demonstrating the large amount of sound energy available in the reproducing equipment.

To those interested in the reproduction of satisfactory music, perhaps the most interesting features of the demonstration were the feeling of depth of sound produced by the directional effect, and the independent control of sounds of different frequencies and origins which were shown to be available.

A.I.E.E. Board Urges That Activities of U.S. Bureau of Standards Be Maintained

The following resolution was adopted by the Institute's board of directors on January 22, 1934, at its meeting held during the Institute's recent winter convention in New York, N. Y.

Whereas the American Institute of Electrical Engineers is a professional society of 16,000 members engaged in promoting the electrical art and

Whereas a necessary and fundamental part of the art is the determination and maintenance of fundamental standards and tests and

Whereas this essential work has been done by the Bureau of Standards under this authority of congress for many years as part of an expanding national and international program to

(*a*) determine and maintain the value of the ampere, the volt, and the ohm

(*b*) improve the physical standards of resistance

(*c*) maintain and improve standard cells

(*d*) maintain, devise, and improve measuring methods and devices for current, voltage, light, magnetism, insulation, frequency and other fundamental elements in the electrical field; and

Whereas this work conforms to the original purpose for which the Bureau was established and has been done so well as to gain it national and international favor and reputation and

Whereas the American Institute of Electrical Engineers believes this work to be of great scientific value and necessary to practical advances in electrical engineering and improvements in the electrical industry and

Whereas, as a consequence of the retrenchment policy of the Federal Government, those activities of the Bureau of Standards have been curtailed drastically, which has resulted in serious detriment to the art and the industry

Be It Resolved, therefore, that the attention of proper committees and members of Congress be called to this critical situation with the request that in making appropriations for the coming fiscal year, provision be made for the necessary and adequate technical standardization and research activities of the Bureau of Standards in the electrical field so that it may continue its valuable contributions to the art and industry and

Be It Further Resolved that copies of this resolution be sent to other technical societies similarly concerned with the scientific work of the Bureau of Standards and to the American Engineering Council with the suggestion that they also survey this critical situation with the view of taking similar action.

Plans Progressing for Institute's Fiftieth Anniversary Celebration in May

ORGANIZED May 13, 1884, the American Institute of Electrical Engineers will, on May 13, 1934, complete a half century of constructive professional and public service. As reported on p. 931 of ELECTRICAL ENGINEERING for December 1933, suitable commemoration of this anniversary date has been under consideration by Institute officers and committeemen for some time, and has been segregated definitely into 3 general classifications:

1. An enlargement of the May 1934 issue of ELECTRICAL ENGINEERING and the conversion of that issue into a special anniversary number containing a wide variety of material of historical significance and importance to the Institute and to the profession.
2. Special meetings that are being planned by many Sections and Branches to commemorate not only the Institute's 50th anniversary but also the anniversary of the organization of the Section or Branch.
3. A special program to be presented in connection with the annual summer convention at Hot Springs, Va., June 25–29, 1934.

A meeting of the anniversary committee was held in New York, on Wednesday, November 22, and since that time the plans have been developing rapidly. Principal contributors to the anniversary issue will be the 25 living past-presidents of the Institute, 2 of whom are among the 6 living charter members of the Institute. From the wealth of experience accumulated by these professional leaders will come a group of powerful articles, some dealing with important matters in electrical history, some with colorful personal reminiscences, some with special technical phases of the art and their significance, some with the Institute's organization and development, and some with the experiences and expectancies of electrical engineers in the realm of education, government, and human relations.

With respect to the annual convention in June, it is contemplated that an inspiring program in celebration of the anniversary will be developed and built around the living charter members of the Institute and all of its past-presidents, many of whom it is hoped will be present there.

Space available in this issue precludes the possibility of going further into detail at this time. However, further and more complete information is scheduled for publication in later issues of ELECTRICAL ENGINEERING.

An Appeal for Papers on Industrial Power Applications

RECOGNIZING the difficulty of securing suitable articles and papers for publication on the subject of industrial power applications, the Institute's technical committee on general power applications under the chairmanship of M. R. Woodward is making a well organized attempt to secure papers describing particular cases of industrial power applications which should be of interest to members in this field. The stimulation of such papers has been assigned to an editorial and review subcommittee under the chairmanship of A. E. Knowlton. Following the acceptance of the chairmanship of this subcommittee by Mr. Knowlton, one of his first acts was the circulating under date of December 5, 1933, of a letter to all members of the committee on general power applications, urging their coöperation in the securing of papers of industrial power applications.

Since there are many members of the Institute not members of this committee, but fully qualified to assist in its work, this matter was considered worthy of being brought to the attention of the entire membership through the columns of ELECTRICAL ENGINEERING. The following excerpts are from this letter to the members of the committee:

"In your practicing or consulting contacts with industrial users of electrical power and equipment have you not learned of at least one worth-while accomplishment in the realm of the industrial engineer? Especially desirable would be a paper from the engineer himself in contrast to one from the electrical manufacturer who made the installation. There have been many of that type and more are to be available. If each committee member will turn in one live lead of this nature it would assuredly put the committee in a position to discharge its manifest duty along these lines.

"Fourteen and one-half per cent of the A.I.E.E. members are classified occupationally as industrial (other than electrical manufacturing, which represent 20 per cent). It is presumed that these members have a desire and a right to hear and see presented papers that pertain to their field of activity in electrical engineering. Of the 21 papers on hand at A.I.E.E. headquarters ready for publication, 2 were listed as having appeal to industrial electrical engineers but neither of them was from a practicing industrial electrical engineer. Of the papers promised or proposed only 1.4 per cent could be classed as having occupational appeal to industrial electrical engineers.

"It is evident that the $^1/_7$ of the membership represented by this group is not receiving in return by way of specific literary contributions anywhere near its due. . . . . . I believe it is incumbent on the committee on general power applications to make a determined effort to correct this situation in the interests of the Institute and of the professional status of its members in industrial electrical pursuits.

"In the last analysis there can be only 3 obstacles to the production of an adequate number of power application papers:

1. Industrial electrical engineers make no creative contribution to the electrical art.
2. Even if they do so, they do not have the aptitude for recording their accomplishments in print.
3. Even if they did have the aptitude, they would not be allowed by their superiors to exercise it.

"In my belief the third is the dominant obstacle, and therefore the one to be attacked. Until this is overcome to the extent that chemical, mechanical, metallurgical and other engineers have overcome it, the electrical engineer in the industrial plant will lag in relative professional status.

"In asking you therefore to volunteer information as to prospective sources of papers I ask you to have this broad objective in mind as well as the immediate objective of balancing the paper program of the Institute."

Suggestions which may be made by members of the Institute in accordance with this request should be addressed to A. E. Knowlton, chairman, editorial and review subcommittee, care of *Electrical World*, 330 West 42nd Street, New York, N. Y.

Columbia University Offers E.E. Scholarships

The governing bodies of Columbia University have placed at the disposal of the A.I.E.E. each year, a scholarship in electrical engineering in the school of engineering of Columbia University for each class. The scholarship pays $350 toward the annual tuition fees which vary from $340 to $360, according to the details of the course selected. Reappointment of the student to the scholarship for the completion of his course is conditioned upon the maintenance of a good standing in his work.

To be eligible for the scholarship, the candidate recommended will have to meet the regular admission requirements, in regard to which full information will be sent without charge upon application to the secretary of the University or to the National secretary of the Institute, 33 West 39th St., New York, N. Y.

In a letter addressed to the national secretary of the Institute, an applicant for this scholarship should set forth his qualifications (age, place of birth, education, reference to any other activities, such as athletics or working way through college, references and photograph). A committee composed of W. I. Slichter, *chairman*, Francis Blossom, and H. C. Carpenter will consider the applications and will notify the authorities of Columbia University of their selection of a candidate. The last day for filing of applications for the year 1934–35 will be June 1, 1934.

The course at the Columbia school of engineering is a graduate course which may be either elective leading to the degree of master of science or prescribed leading to the degree of electrical engineer. For the former, requirement for admission is the completion of a 4-year course in electrical engineering as evidenced by a bachelor's degree from an approved institution. For

the professional degree, the requirements are more specific as to course content and include a considerable proficiency in mathematics, physics and chemistry, and some knowledge of the humanities, as well as the usual undergraduate technical courses. The candidate is admitted on the basis of his previous collegiate record without undergoing special examinations. Other qualifications being equal, members of the Student Branches of the A.I.E.E. will be given preference.

The purpose of this advanced course is to produce a high type of engineer, trained in the humanities as well as in the fundamentals of his profession. It is hoped that enrolled students and others qualified will show a keen interest in this scholarship.

Boulder Dam Visited by San Francisco Engineers

AN interesting inspection trip through Boulder Dam was made early in December by 52 engineers under the auspices of the San Francisco (Calif.) Engineering Council. Leaving San Francisco on special cars Friday morning, December 8, Saturday and Sunday were devoted to inspection, the return being completed Monday evening. The following excerpts from a report prepared by H. W. Crozier (A'03, M'12) should be of interest to all engineers, reflecting as they do some of the most important features at Boulder Dam:

The deep canyon of the Colorado was a hive of industry. Concrete is being placed night and day so steadily that the dam has now risen 150 ft from the rocky bottom of the river and is just a little above the level of the water in the river. Great cableways spanning the canyon are used to lift the big buckets of concrete for the dam, and one of them, the largest ever made, will be used to place the machinery and be retained permanently.

The gravel pit, aggregate washing and classification plant, high-mix and low-mix concrete plants were visited. The Nevada spillway, cableways, diversion and power tunnels were inspected and an opportunity was given every one to see all details of the placing of concrete in the dam, the refrigerating system of pipes for heat extraction, and intake tower and powerhouse foundation work in progress.

The Colorado River, which filled the 4 50-ft by-pass tunnels within a few feet of their tops during the high water in June, had shrunk so low in December that one tunnel only was needed to carry the water. The engineers went through the other tunnels and inspected the work of preparing to lower the great steel stop gates and place the concrete plugs to stop the water forever. The tunnels for the pipes which will deliver the water to the great turbines and the preparation of the powerhouse foundations were also scenes of activity.

As the dam rises the removal of the heat resulting from the setting of the cement becomes an important problem because of the enormous mass of the dam, and one which has heretofore never been encountered on such a large scale. This problem has been successfully solved by a system of pipes, placed in the dam before pouring the concrete, in which ice cold cooling water, produced in a special refrigeration plant, is circulated. This system for removing the chemical heat released during the setting of the concrete, is used for the first time at Boulder Dam and is one of the most interesting and successful features of the great project.

Also interesting was the large pipe welding plant of the Babcock and Wilcox Company where steel plates 3 in. thick are being rolled into pipes and the seams electrically welded. Machines welding pipes 9 ft up to 30 ft in diameter were in operation, and miles of seams must be welded in the next 2 years before all the pipes are made and placed in position. (Editor's Note: See ELECTRICAL ENGINEERING, September 1933, p. 644, for a further description of the field fabricating plant.)

Every foot of welded seam is inspected by an X ray machine, the most powerful ever devised, and a picture made through the steel on a photographic film 4 in. wide and 14 in. long. The photographs are so clear that a perfect job is assured, because no defect can escape the all-seeing eye of the X ray. (Editor's Note: See ELECTRICAL ENGINEERING, May 1933, p. 349, for a further description of these X ray units.)

One of the most delightful features of the trip was the way the inherent faculty of the engineers for management and planning manifested itself when they organized their excursion for their own convenience and comfort, as one of those smoothly running machines that apparently run themselves. Dividing the tasks of looking after the sustenance, housing, and direction of the sightseeing among themselves by a scheme of committees, nearly all members of the party accepted responsibility for some part of the job of running things, and were ably assisted by the efficient coöperation of the Santa Fe organization, with the result every one had ample leisure to devote to the important job of sightseeing.

The *Las Vegas Age*, in commenting on the concluding dinner of the trip, says, in part:

"W. B. Young was introduced as the second speaker and gave a most interesting discussion of the project. He entered upon some of the phases of the work and the results to be expected. Speaking of the silt problem, he stated the probability that it would require 300 years for the deposit of silt to fill the reservoir, provided there were no dams constructed in the upper river. In 50 years amortization period of the project, the reservoir would contain only 300,000 acre feet of silt, only $^{1}/_{10}$ of its capacity. He said that the reservoir, when completed, will become a national asset because of its peculiar scenic attractions.

"Describing the power plant, he stated

Two interesting views of the Boulder Dam project taken during the recent visit of 52 San Francisco engineers to Boulder Dam for an inspection of the many unusual features involved

that the generators to be installed in the powerhouses would generated 1,835,000 hp, and that there will be 663,000 hp of firm or primary power.

"The time for the completion of the project was originally set for April 1938. Through the energy of the Six Companies, Inc., who have advanced the work until it is 15 months ahead of schedule, the dam proper will be completed in May or June 1935 and it will be possible to generate some power September 1935. Because of the massiveness of the generators, 40 ft in outside diameter, the power installation will not be completed until after this date. There will be 17 power units installed, 15 of which will be of 115,000-hp capacity. Four of these larger generators and one smaller one have been contracted for and are under construction."

Annual Meeting of U.S. Committee on Illumination

The 1933 annual meeting of the United States national committee of the International Commission on Illumination was held in New York, N. Y., November 8, 1933. Officers were elected, committee appointments were made, and the annual report of the president was presented.

An extended review of technical committees and other activities indicated substantial progress in the United States in preparation for the plenary session, scheduled for Germany in 1935.

L. B. Marks (A'90, F'12 member for life) wa selected honorary president, U.S. National Committe. E. C. Crittenden (A'19, M'22) and G. H. Stickney (A'04, F'24) were reëlected respectively as president and secretary-treasurer. They were also reëlected as United States members of the I.C.I. executive committee, of which committee C. H. Sharp (A'02, F'12, member for life), vice-president of the I.C.I. is also a member. J. W. Barker (M'26, F'30) P. S. Millar (A'03, M'13) and L. A. S. Wood (M'24) were appointed to serve with the officers on the (United States) executive subcommittee.

The 3 U.S. secretariat committees were reappointed. As U.S. representatives on technical committees, P. S. Millar was appointed for No. 4 glare (streeting lighting); L. A. S. Wood for No. 23(*a*), street lighting; W. F. Little for No. 23(*b*) automobile lighting. All other technical committee representatives were reappointed.

E. C. Crittenden was appointed representative on the division of foreign relations, National Research Council and L. A. S. Wood was appointed auditor of the national committee.

Annual Report Presented

At the annual meeting, on November 8, Eugene C. Crittenden (A'19, M'22), president of the committee, presented his annual report. A brief summary of this report follows:

Developments during the past year have emphasized the difficulty involved in carrying on international activities like those of the International Commission on Illumination, but have at the same time shown the importance of maintaining American participation in them. It has been found expedient to postpone for a year the session of the commission, originally scheduled to be held in Berlin in 1934, and the illumination congress which is to be coupled with it. Nevertheless, some of the technical work of the commission has made notable progress, and the results obtained are of material importance to the lighting industry in America as well as abroad.

The activities in which most definite progress has been made are the fundamental problems of measurement, in which international standardization is highly desirable. Work initiated by the commission now gives promise of bringing about world-wide uniformity in units and standards of light and in the method of specifying colors. Discussions are also under way on physical photometers and on the evaluation of ultraviolet as an adjunct to lighting.

The International Committee on Weights and Measures is the legal agency established by treaty among 32 nations to direct all metrological work which the governments concerned desire to have carried on jointly. By a recent amendment to the treaty, electrical units and standards were placed under the jurisdiction of this committee, and this extension of authority has been construed to include photometry. However, the committee operates under the authority of a general conference on weights and measures, which, in authorizing the establishment of an official international advisory committee on photometry in October 1933, stipulated that in the choice of its members special consideration shall be given to the personnel of the special committee on units and standards of light established by the International Commission on Illumination in 1931.

Continuation of the work of various committees of the I.C.I. previously reported has been carried on throughout the past year, and considerable progress has been made toward the next session of the commission and the illumination congress. Increased interest in this work, however, was urged.

Distribution of the 2-volume Proceedings of the 1931 Congress continues in a satisfactory manner.

The financial status of the national committee is satisfactory for the present, but the dissolution of the National Electric Light Association combined with changes in the rate of foreign exchange, will make the annual expenses greater than the income. Business or industrial interests concerned with the development of lighting are considered as the most likely sources of additional support.

Novel Use of Electrical Illumination

An unusual use was made of electrical illumination this past Christmas season when 22,000 watts of electricity were used to light the Gothic ice chapel building on the campus of Lawrence College, Appleton, Wis. The entire chapel, which is 23 ft long, 14 ft 7 in. wide without the side buttresses and 18 ft high to the ridge pole, is constructed entirely of ice with the exception of the roof which is overlain with evergreen branches. The chapel was built following a modified Gothic design, and was so constructed that the lights which were used in the night illumination had varying effects according to the thickness of the walls. All of the reflectors and lighting effects were designed and built under the supervision of W. E. Schubert, chief engineer for the Wisconsin-Michigan Power Co. The large unit reflectors gave off their illumination through a straight reflector system for the larger lights and a flasher system for the smaller lighting. The great amount of heat generated by this battery of lights made it necessary to cover the roof with evergreen branches so that ample ventilation could be provided for. The ice chapel is intended as a permanent event for each Christmas season.

Bureau of Standards Reports Electrical Work

In the annual report of the Secretary of Commerce of the United States the principal projects undertaken by the Bureau of Standards in 1933 are summarized. Items appearing under the heading "Electricity" are reprinted in the following paragraphs because of their interest to various members of the Institute:

1. New basis for electrical units. Determinations of values for the ampere and the ohm by absolute measurements were continued. In the case of the ampere, the average value from results to date is 1 B. S. international ampere = 0.999941 absolute ampere. Values for the ohm are derived from calculated inductances of carefully constructed coils, several of which have been built at the Bureau in recent years. The value (subject to slight corrections) of 1 B. S. international ohm as determined by various coils is:

From the procelain coil: 1.000463 absolute ohms.
From the quartz coil: 1.000442 absolute ohms.
From the pyrex glass coil: 1.000455 absolute ohms.

2. Standards of electrical resistance. Eighteen one-ohm resistance standards of the type recently developed at the Bureau were constructed, and appear to be of exceptional quality. They will probably be used in future, international comparisons, as well as in the maintenance of the unit in the United States.

3. Standards of electromotive force. Improvements in the constancy of the Weston normal cell as a standard of electromotive force have been made possible by the use of materials for the containers which are more inert chemically than those previously employed. A new high precision potentiometer for the comparison of standard cells was constructed and placed in service. Comparisons were made of the Bureau's standards of electromotive force with those of England, France, and Germany.

4. Large absolute electrometer and equipment for testing of current transformers. A number of mechanical improvements have been incorporated in the Bureau's absolute electrometer, and results are now attainable with a precision of a few hundredths of one per cent. The equipment for testing current transformers has been put into commission and has been found satisfactory for tests up to 12,000 amp.

5. Magnetic testing and research. An apparatus for magnetic testing at high magnetizing forces was developed and has been added to the list of approved methods of the American Society for Testing Materials. A magnetic balance was developed for the inspection of austenitic steel. Apparatus was constructed for the application of the "magnaflux" method to the inspection of hollow steel airplane propellers and proved very effective in the location of hidden defects.

6. International standards of candlepower for commercial types of electric lamps. The national laboratories of France, Germany, Great Britain, and the United States have now agreed to bring their standards of light for the commercial types of lamps into accord through the use of visibility factors established by measurements at the Bureau and accepted by the International Commission on Illumination. Values of the colored filters to serve this purpose have been adopted and each participating laboratory has received one of the filters.

7. Primary radio-frequency standard. The Bureau's primary standard of radio frequency was improved and is now automatically protected against power failures.

8. Secondary standards of radio frequency. A semiportable piezoelectric standard was developed to maintain a frequency constant within 1 part in 10,000,000 for several hours without adjustment. A new type of toroidal quartz plate was developed with marked advantages in respect to temperature coefficient and constancy.

9. Dissemination of standard radio frequency. The accuracy of the 5,000-kc radio transmissions was increased to 1 part in 10,000,000. Greater reliability was brought about by a change from 1 to 30 kw in the power of the transmitter and by the development of highly accurate automatic monitoring procedure. The standard frequency signals were made available to the public over wire line connections.

10. Measurements of radio wave variations. Equipment for the automatic recording of received wave intensities was installed and applied to a study of the relative values of different frequencies for broadcasting. The data aided directly the work of 2 international radio conferences (Madrid, 1932, and Mexico City, 1933). Radio transmissions at the lower and the higher frequencies were correlated with solar data and terrestrial magnetic changes. Equipment was developed for a fundamental study of direction and polarization phenomena.

11. Height of ionized layers. Automatic recorders were developed and used for determining the varying heights and ionization of the layers in the upper atmosphere which make possible long distance radio transmission. Part of this work was in connection with the world-wide polar year program of scientific measurements.

12. Storage batteries. It was found that gradual corrosion of the positive grids of storage batteries under ordinary conditions may liberate enough antimony to increase materially the rate of sulphation of the negative plates. Determinations have been made of viscosity and resistivity of sulphuric acid solutions at low temperatures, which will aid in predicting the operating characteristics of storage batteries under severe climatic conditions. Mechanical, electrical, and chemical properties of storage battery separators have been measured for the Navy Department, to determine the suitability of different kinds of wood, both treated and untreated, and the variation of these properties in commercial practice.

13. Insulating properties of rubber. A complete study of the dielectric constant, power factor, and resistivity of rubber-sulphur compounds at temperatures from −75 deg to +150 deg C, and under various pressures, has been completed.

14. Telephone engineering service. Three Government departments and other establishments were advised as to the most economical and efficient methods for supplying telephone and related services in their buildings.

15. Electrical and other safety codes. Bureau representatives have assisted in revision of the National Electrical Code. Handbook no. 17, containing a revision of the code for protection against lightning, was issued, and a model ordinance for electrical inspection was prepared. Two documents on construction of power lines were prepared for the International Electrotechnical Commission. Members of the staff participated in the Annual Safety Congress and in the work of the safety code correlating committee, and assisted State officials and various committees formulating and revising safety codes.

16. Prevention of underground corrosion. The successful use of bituminous coatings on pipe lines requires the setting up of recognized methods for identifying the materials used, and for determining their properties and performance. Two methods for determining the condition of bituminous coatings after service have been developed in coöperation with the American Gas Association and American Petroleum Institute. A laboratory method for determining the resistance of coatings to soil stress, the principal cause of coating failures, is being developed.

Officers of the Institute of Radio Engineers. The list of officers and members of the board of directors of the Institute of Radio Engineers to serve for the year 1934 has now been announced. C. M. Jansky, Jr. (A'20, M'32) Washington, D. C., was elected president and Balth van der Pol, Eindhoven, Holland, was elected vice-president. The following were elected as members of the board of directors: A. N. Goldsmith (M'16, F'20) New York, N. Y., Arthur Batcheller, New York, N. Y., and William Wilson (M'23) New York, N. Y. In addition to these elected directors, the following were appointed to serve as members of the board of directors: Melville Eastham A'19, M'26) Cambridge, Mass., H. P. Westman, New York, N. Y., J. V. L. Hogan (A'11, M'20) New York, N. Y., L. C. F Horle (A'20, M'22) Newark, N. J., E. R. Shute (M'17) New York, N. Y., A. F. Van Dyke, New York, N. Y., and H. A. Wheeler, Bayside, L. I., N. Y., W. G. Cady (M'19) Middletown, Conn., and L. M. Hull (M'27) Boonton, N. J., both junior past-presidents of the I.R.E., serve as *ex-officio* members of the board. Other members of the board, holding over from previous terms are: O. H. Caldwell (A'13, M'22) New York, N. Y., R. A. Heising (A'15) New York, N. Y., C. W. Horn, New York, N. Y., F. A, Kolster (M'19) New York, N. Y., E. L. Nelson (A'20, M'26) New York, N. Y., and H. M. Turner (M'20) New Haven, Conn.

Historical Information on Engineering Drawing Requested. The Society for the Promotion of Engineering Education through its division of engineering drawing and descriptive geometry is sponsoring the following projects: (1) A collection of material showing the evolution and variety of instruments used in engineering drawing; (2) a collection of old drawings intended to show the development of engineering drafting room practice and of various means of reproduction on engineering drawings; (3) a collection of the work of writers, old and modern, on the subject of drawing and descriptive geometry; and (4) the preparation of a series of bulletin board posters, carrying a portrait and biography of persons prominent in the history of engineering, and excerpts from their writings emphasizing the value to engineers of training in engineering drawing. The bulletin board posters are intended for general distribution through the drawing departments of all the engineering colleges. They are to be posted week by week, and it is hoped that they will add an inspirational touch to the teaching program. Any persons in a position to lend or contribute to any particular collection write at once to H. M. McCully, Carnegie Institute of Technology, Pittsburgh, Pa., stating the nature of their offering.

International Congress for Applied Mechanics to Be Held. The fourth International Congress for Applied Mechanics will be held in Cambridge, England, July 3–9, 1934. The subjects to be discussed will be groups under the 4 general headings: rational mechanics, including vibrations of structures and machines; mechanics of fluids, including turbulence, the boundary layer, heat transfer, and compressible fluids; materials, including elasticity, plasticity, fatigue, and crystal structure; and water waves, including resistance and stability of shops and seaplanes. The applied mechanics division of The American Society of Mechanical Engineers is coöperating with the committee with the idea of coördinating the participation of other American groups in this congress. Inquiries regarding the congress and promises of manuscripts should be addressed to the applied mechanics division of the A.S.M.E., 29 West 39th Street, New York, N. Y. Those intending to participate are invited to intimate as soon as possible the general nature of their manuscripts. Summaries about 300 words, in English, German, French, or Italian, will be required about April 1, 1934. Although

plans are not definitely formulated, it is proposed to publish only the summaries, together with an abstract of the discussions. Authors are therefore to include in their summaries a list of appropriate references. A free of 15 shillings will be payable by all those taking part in the scientific or social activities of the congress. All those who intimate their intention of attending the congress will receive, early in 1934, a further notice giving details of the arrangements.

A Steam Boiler of New Design

A steam boiler of revolutionary design now being manufactured in England at the works of Messrs. Richardsons, Westgarth & Co., of West Hartlepool, is attracting the attention of marine engineers according to the October 1933 issue of *Industrial Britain*. The boiler is described as being the result of years of research and experiment by Messrs. Brown, Boveri & Co., the Swiss engineering firm now in working agreement with Messrs. Richardsons Westgarth.

Known as the "velox," this steam boiler occupies only about one-eighth the space and is only a quarter the weight of ordinary water-tube boiler plant evaporating an equal amount of steam. Starting from cold, it can attain full steam pressure in about 6 min and full output in 8 min.

The principle is the burning of liquid or gaseous fuel under high pressure in order to obtain high flue-gas velocities and the creation of this high pressure by a compressor driven by a gas turbine using the exhaust gases.

The fuel burns at a pressure of 20 lb per sq in. higher than that of the atmosphere. The small combustion chamber is lined with water tubes, inside of which are 3 or more flue-gas tubes through which the gases pass at about 600 miles an hour. Nearly all the energy employed to drive the compressor is recovered in the form of furnace heat and pressure.

A.S.T.M. to Meet in Washington. The 1934 regional meeting of the American Society for Testing Materials will be held in Washington, D. C., March 7, 1934, with headquarters at the Wardman Park Hotel. The technical feature of this regional meeting will be a symposium on outdoor weathering materials and metallic coatings sponsored jointly by the A.S.T.M. committees *A*-5 on corrosion of iron and steel, and *B*-3 on corrosion of nonferrous metals and alloys. The 1934 group meetings of A.S.T.M. committees also will be held at the Wardman Park Hotel, Washington, March 5–9, 1934.

Mining Engineers to Meet. The 143d meeting of the American Institute of Mining and Metallurgical Engineers will be held in the Engineering Societies Building, 29 West 39th Street, New York, N. Y., February 19–22, 1934. A program including a large number of papers on a variety of subjects in the field of mining and metallurgy will be discussed. Perhaps the most interesting of these from the point of view of electrical engineers will be the sessions on geophysical prospecting and nonmetallic minerals, and the meetings of the iron and steel division and the Institute of Metals Division.

Exchange of Professors Being Arranged. Announcement is made that beginning with the next academic year, 1934–35, the Massachusetts Institute of Technology, Cambridge, will inaugurate a general plan for the exchange of professors with other educational institutions in this country as well as abroad. The purpose of this plan is to broaden the experience, acquaintance, and educational outlook of members of the faculty, and to disseminate, quickly and widely the best educational methods as they are developed in the various institutions. In announcing the plan, Dr. Karl T. Compton (F'31) president of M.I.T., states that this plan will tend to overcome any tendency of institutions to become ingrown or isolated. The plan provides for an exchange arrangement each year for one member of the staff of each of the departments of study, embracing the fields of science, engineering, architecture, and humanities.

Report of National Screw Thread Commission Available

Progress in commercial screw thread practice, which is based very extensively upon the standards established by the National Screw Thread Commission, has been such as to require several revisions and some additions to the standards promulgated in the commission's 1928 report. The 4th edition of the report of the National Screw Thread Commission, as approved April 10, 1933, is now available, and is now for sale by the superintendent of documents, Washington, D. C., at a price of 15 cents. This report is miscellaneous publication No. 141.

The initial accomplishment in the standardization of screw threads in the United States was the report under date of December 15, 1864, of a special committee appointed by the Franklin Institute, which recommended a definite thread system. This thread system, adopted as a standard for most lines of work in this country, fulfilled a great need. Later developments, however, required other sizes of screws, and the difficulties encountered in obtaining enormous quantities of war material by the United States government during the World War motivated further standardization of threads. The National Screw Thread Commission was authorized by Congress in 1918, and work started immediately.

In its work of establishing standards for screw threads, the commission has made particular effort to secure actual facts concerning the need of standardization and the economic conditions to be provided for in the production and use of screw threads. Hearings to obtain information were conducted in various industrial centers throughout the country, and extensive use of technical magazines was made in distributing and requesting information. A large number of experiments and tests also were made by the Bureau of Standards, and members of the commission individually conducted experiments and research work at their own expense. The advances made by the commission up-to-date will have tremendous benefit.

In the present report, specifications for threaded products and gauges are included, with sufficient information to permit the writing of definite and complete specifications for the purchase of products. Much supplementary information also is included. The specifications have been arranged, as far as possible, by products, and each section is arranged in the following order: (1) form of thread, (2) thread theory, (3) classification and tolerances, (4) table of dimensions, and (5) gauges.

Psychrometric Charts. Two sets of charts have been developed by the U.S. Bureau of Standards for use in the determination of the pressure of water vapor from psychrometric observations. These charts are based upon the psychrometric formula, one set based upon Fahrenheit temperatures and pressure in inches of mercury, the other upon Centigrade temperatures and pressure in millimeters of mercury; both will give relative humidity in per cent. It is reported that the bureau found in their development that the addition of 2 scales permitted the accurate evaluation of relative humidity as well. In comparison with the customary double interpolation tables it has been found that the use of these charts increased the precision and halved the time required. This 4-page leaflet, Bureau of Standards Miscellaneous Publication No. 143, is for sale by the Superintendent of Documents, Washington, D. C., at 5c per copy.

Domestic Short Wave Radio Communication. In speaking before the Advertising Club of New York, January 16, David Sarnoff, president of the Radio Corporation of America, announced that his company is about to develop a domestic short wave radio communication system through the establishment of stations at Boston, New York, New Orleans, San Francisco, and Chicago, together with such necessary relay stations as may be required to provide an effective communications network. It was announced that the proposed system will "constitute the beginning of the end of the dot-and-dash system of commercial communication." It is expected that transmission speeds of 180 words per minute will be provided by multiplexing the channels, and that facsimile transmission of written or photographic copy will become the order of the day.

American Physical Society to Meet in New York. The 190th regular meeting of the American Physical Society will be held in New York, N. Y., on Friday and Saturday, February 23 and 24, 1934, as a joint meeting with the Optical Society of America. All sessions will be held at Columbia University in the physics laboratories.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Potential Available for Gaseous Discharge in Insulation Voids

To the Editor:

It is an all too common misconception that the field in a gaseous bubble or void in an insulating material of specific inductive capacity ϵ may be obtained simply by multiplying by ϵ the field that is known to exist at that point in the absence of the void. This is true only if the void has the shape of a flat slab of infinite extent, and only approximately true in that case. In general the larger is ϵ and the smaller the relative dimensions of the void in directions perpendicular to the field the more pronounced is the error in using this abstraction. The error is considerable if the voids are spheres, for example.

I present here the appropriate solutions for general ellipsoids of semiaxes a, b, and c, where a is in the direction of the field, and of several special cases, such as spheres ($a = b = c$), infinite elliptical cylinders perpendicular to the field ($c = \infty$) and flat slabs ($b = c = \infty$). These cases cover, at least approximately, all of the common shapes encountered in voids in oil and paper insulated cable, for example. A butt space void may be closely approximated by an infinite elliptical cylinder, wherein the paper thickness is $2a$ and the butt spacing $2b$.

These solutions are obtained by the method outlined in Mason and Weaver's book "The Electromagnetic Field" (University of Chicago Press, 1929), and may be given in general terms by virtue of the fact that the field is everywhere constant inside voids of these shapes. Indeed, this fact is the essence of the method used to obtain the solutions. In the case of a rectangular parallopiped, for example, the field is not constant throughout the void, the solution is difficult to obtain, and may not be expressed in general terms. The solutions are:

$$E_1 = \frac{\epsilon_2 E_0}{\epsilon_1} \quad \text{infinite plane slab}$$

$$E = E_0 \frac{3\epsilon_2}{\epsilon_1 + 2\epsilon_2} \quad \text{sphere}$$

$$E_3 = \frac{E_0}{1 + \dfrac{b(\epsilon_1 - \epsilon_2)}{\epsilon_2(a + b)}} \quad \text{infinite elliptical cylinder}$$

$$E_4 = \frac{E_0}{1 + \left\{\dfrac{\epsilon_1}{\epsilon_2} - \epsilon_1\right\} \dfrac{abc}{2} \displaystyle\int_0^\infty \frac{dn}{(a^2+n)\sqrt{(a^2+n)(b^2+n)(c^2+n)}}} \quad \text{general ellipsoid}$$

where E_1, E_2, E_3, and E_4 are the fields in voids of the shapes indicated, E_0 is the field that would exist at the center of the void in the absence of the void, ϵ_2 is the specific inductive capacity of the insulating medium and ϵ_1 is the specific inductive capacity of the material in the void, unity if this is a gas.

It is assumed, in obtaining these solutions, that the field remains undisturbed far from the void. In the case of the sphere it can be shown by the method of images, that the solution is affected to a negligible extent until the sphere is within its own diameter from an electrode. When this occurs the available field is less, lying between E_0 and E_2. These values E_1, E_2, E_3, and E_4 are therefore all maximum values and E_0 is the lower limit, if $\epsilon_2 > \epsilon_1$.

In the case of an infinite slab between parallel electrodes, the electrode effect may be easily derived. If we divide the space between electrodes into 3 slabs of thickness t_1, t_2, and t_3 with specific inductive capacities of ϵ_1, ϵ_2, ϵ_3, respectively, and with the field $E_0 = -\dfrac{V}{d}$ (V is the potential between plates and $d = t_1 + t_2 + t_3$), the correct expression for E'_2, the field in the void, is

$$E'_2 = \frac{E_0 d}{\epsilon_2} \frac{1}{\dfrac{t_1}{\epsilon_1} + \dfrac{t_2}{\epsilon_2} + \dfrac{t_3}{\epsilon_3}}$$

This degenerates into the form of E_1 of the discussion above only if $t_2 = 0$. If $t_2 = t_3 = 0$, then $E'_2 = E_0$, the limiting case when the void fills the entire space between electrodes.

Thus the shape of the void may be a very important factor in a discussion of the possibility of a discharge occurring in it. These considerations must be taken into account in any theory of liquid breakdown that supposes discharges in gas bubbles, in the form of spheres or perhaps long needles in the direction of the field (in which case the field would not differ sensibly from E_0).

To gain an idea of the magnitude of this correction, suppose $\epsilon_1 = 1$, $\epsilon_2 = 3$ in the case of a sphere. Then $E_2 = 1.3E_0$ as compared with $E_1 = 3E_0$ for a thin flat slab.

The above was presented before a meeting of the insulation committee of the National Research Council, Philadelphia, Pa., November 15, 1933.

Very truly yours,

EDWARD B. BAKER

(Office of C. F. Hirshfeld [A'05], The Detroit Edison Co., Detroit, Mich.)

Jogging the Rotor of an Alternator Electrically

To the Editor:

It sometimes happens that it is necessary to uncouple a generator from its turbine to make tests, check up on shaft alignment, or for some other reason. After the generator has been motored, the rotor seems, invariably, to come to rest about 180 deg from its correct position. This, of course, is the worst condition but the probability of bringing the rotor to rest in approximately its right position is very remote, hence it is usually necessary to jack the rotor into position by some mechanical means. With some machines this is not much of a problem but with large alternators it is a big chore. Where there is a spare exciter set, exciter, or excitation bus available in the power house it is possible to use the direct current to turn the rotor into its correct position by one or other of the following methods with very little work.

When the generator has its neutral brought out the arrangement shown in Fig. 1 is probably the easiest and simplest. One of the field leads is connected to the neutral, the other to the source of excitation through the field contactor. The terminals T_1, T_2, T_3, are brought to disconnecting switches, the other poles of which

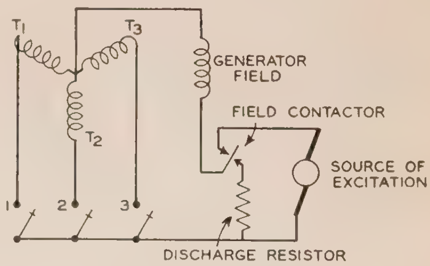


Fig. 1. Method 1

are connected together and to the other side of the source of excitation. If the inductance of the stator winding is not too great it is usually possible to move the rotor around to its required position, 60 electrical degrees at a time, by operating the disconnecting switches alone without at any time opening the field circuit. Starting with phase 1 closed, close the field contactor, then close phase 2, open phase 1, close phase 3, open phase 2, close phase 1, open phase 3 and continue until the rotor comes around to its proper location where the circuit is completely deënergized by means of the field contactor. By following this procedure the field circuit is not opened and it is usually possible to operate the disconnecting switches without particularly bad sparking if it is done slowly. If the sparking is such as to be detrimental to these switches the operation can be performed by the help of field contactor connecting the phases consecutively 1, 2, and 3, closing and opening the circuit by the field contactor, thus bringing the rotor around 120 electrical degrees at a time. In the majority of cases this method of jacking around the rotor does not involve any special switches as it is usually possible to open the line breaker and make use of the

disconnecting switches between the breaker and the generator.

In cases where the generator neutral is not available or where the ampere turns in one leg of the stator winding is not sufficiently great to pull the rotor around, method 2, Fig. 2, can be used. This method, while not requiring a neutral, has the disadvantage of requiring double throw disconnecting switches which are not always as readily available as the single throw disconnecting switches. With this connection

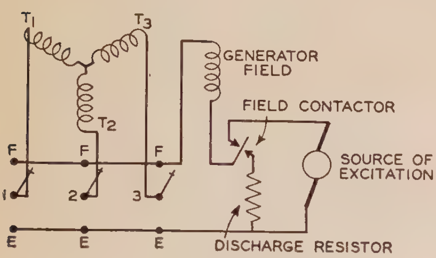


Fig. 2. Method 2

it is possible to bring the rotor around 30 electrical degrees at a time by operating the switches alone without opening the field circuit. Starting with 1-*F* and 2-*E* closed, close the field contactor, then close 3-*E*, open 2-*E*, close 2-*F*, open 1-*F*, close 1-*E*, open 3-*E*, close 3-*F*, open 2-*F*, close 2-*E*, open 1-*E*, close 1-*F*, open 3-*F*, close 3-*E* and continue until the rotor comes around to its required location where the circuit is completely deënergized by means of the field contactor. If this operation causes too much sparking on the switches the rotor can be brought around, as in method 1, by throwing the switches consecutively in positions 1-*E*, 2-*F*; 2-*E*, 3-*F*; 3-*E*, 1-*F*; and closing and interrupting the circuit through the field contactor.

The results of practical experience with these methods in moving around the 300-ton rotors of some 50,000-hp generators showed that with this method it was possible to accomplish in an hour's time with 2 men that which would have required a crew of 6 men 12 hr to do by mechanical means. It was found to be possible, due to the fact that the static friction of the bearings is much greater than the running friction, to advance the rotor several pole pitches at a time by changing the connections for a 120-deg phase advance and closing and quickly opening the field contactor. If the field is left applied the rotor will usually oscillate in its new position several times before coming to rest, but sometimes with a 120-deg phase advance it will jump 2 pole pitches before coming to rest. Thus, if the field is interrupted just as the rotor starts to move, it is possible to make use of the stored energy in the rotor to move it several pole pitches instead of it being used up in oscillation.

By using the first method it is possible to bring the rotor to rest within plus or minus 30 electrical degrees of its required position; with method 2 it is possible to come within plus or minus 15 electrical degrees. As the last few mils in either case has to be obtained by means of a hydraulic jack, method 1 is usually close enough, but if a little closer alignment is required a movement of 30 electrical degrees on either side of the final position may be obtained by shifting the field cable from the neutral to one or other of the phases which is not closed through the disconnecting switch; thus if phase 3 is closed, shifting the neutral cable to phase 1 or 2 will advance or retreat the rotor 30 electrical degrees, leaving the rotor within plus or minus 15 electrical degrees of its required position.

The movements in this article have been described in electrical degrees. To bring any movement in electrical degrees to mechanical degrees multiply by 2 divided by the number of poles. Thus in a 40-pole generator 30 electrical degrees is $\frac{30 \times 2}{40} =$ 1.5 mechanical degrees, in a 96-pole generator it would be $\frac{30 \times 2}{96} = 0.625$ degree mechanical, which would be $^1/_3$ of an inch on a 56-in. diameter coupling. Hence, it is within $^1/_6$ of an inch ahead or back of its desired position.

When making these connections with either method 1 or 2, care has to be observed to make sure that the discharge resistor is still across the windings, otherwise punctured field insulation may result.

While this procedure was evolved originally for realigning couplings it may be that it can be used efficaciously with any synchronous machine connected to its prime mover or load for jogging the rotor around for inspection, examination of clearances, timing of valves, injection pumps, etc., of reciprocating engines, replacement of pistons, piston rings, etc.

Very truly yours,
H. R. Sills (A'24, M'31)
(A-C Engineering Dept., Canadian General Electric Co., Ltd., Peterboro, Canada)

Engineering Schools and the Changed Conditions

To the Editor:

In his letter "Engineering Schools and the Changed Conditions" appearing in Electrical Engineering for December 1933, p. 936–7, Professor Brainerd of the Moore School of Electrical Engineering, University of Pennsylvania, strongly advocates the rigid curriculum in preference to the elective or liberalized curriculum which has been adopted by the engineering school at Harvard University and which was described briefly by me in an earlier letter to Electrical Engineering (September 1933, p. 647). I believe that it would be regrettable if engineering education should become standardized. A rigid curriculum possibly may produce the better educational results in some schools, whereas other engineering schools may find that the liberalized curriculum is best adapted to their needs. In education, which cannot be reduced to any formula and which should always be adapting itself to changing conditions, it is only by continual experimenting based upon experience that the best methods are ultimately determined.

Professor Brainerd draws from my letter the conclusion that with the liberalized curriculum, fundamentals are sacrified. I did not intend to convey this impression because it is just contrary to our actual experience and intent. In the first place, it is my belief that in engineering education, "fundamentals" is a very much overworked word and too many times it covers a multitude of educational sins. However, if it be assumed that the teaching of fundamentals means the establishment of engineering phenomena by means of the few basic laws of science, even advanced professional courses cannot be taught, except perhaps in a very superficial manner, without continual reference to "fundamentals." For example, it is not possible to give properly a course in a-c machinery, power transmission, or vacuum tubes without continual reference to such basic laws as Coulomb's law, the law governing the attraction and repulsion of magnetic poles, the Biot-Savart law, Ohm's law, the basic law of electromagnetic induction, electron mobility, etc. In an advanced graduate course in high voltage engineering, which I give, even the more complicated capacitive relationships in high voltage circuits are derived directly from Coulomb's law; throughout the course reference is made to this and to other simple laws in the derivations of the more involved electrostatic laws. To my mind, no professional course in electrical engineering is properly given if reference to the so-called fundamentals is not frequent and continuous.

Moreover, it is our experience that students do not actually learn their "fundamentals" in the so-called fundamental courses, but they merely become very slightly acquainted with them. It is only by continual application in the more advanced professional courses that students even begin to make such laws of their own. It is significant that many students inform us of the excellent training in mathematics which they receive from courses in electrical engineering. The reason is that by frequent application to concrete problems, the student finally understands and gets the ability to use the mathematical principles with which he could become only slightly acquainted in the short time allowed for the mathematics course itself. The teaching of so-called fundamentals does not depend upon the content of the curriculum, but on the engineering teacher himself.

Professor Brainerd undoubtedly infers that in the liberalized curriculum the student will fail to elect the basic courses in mathematics and the sciences, but will complete his curriculum with perhaps more general subjects. We find that just the opposite occurs. As a rule, the engineering student, in his attempt to crowd an engineering education into the standard 4-year period, elects the science courses at the expense of the cultural and more general courses, since he feels that his professional success depends almost entirely upon an adequate training in the applications of mathematics and science to engineering problems. To be specific, I find that a number of our students now elect voluntarily a course, "Introduction to Atomic Physics," in their second year, a course formerly not required in the fixed curriculum. This tendency to specialization may be criticized in that it tends to make the engineering student a narrow technician rather than a more broadly trained engineer. However, as most of us are aware, it is

lifficult if not impossible to produce simul-taneously the well-trained technician and the more broadly educated man within the standard 4-year period. (In our program students must of necessity elect a certain number of cultural or general subjects, particularly in the first 2 years, since their preparation is sufficient only for a limited number of the technical courses.)

However, in the well-chosen liberalized program, the student cannot omit the basic courses. For example, as a freshman he may decide that he is interested in the 2 professional subjects, power transmission and a-c machinery. He must plan his course of study so that he will be prepared to take these subjects, probably in his fourth or fifth year. Accordingly, he would elect the following sequence of prerequisites:

Mathematics through the introduction to the calculus
Physics
Mathematics through the calculus
Electricity and magnetism or electrodynamics
A-c theory
(Power transmission; A-c machinery)

The foregoing prerequisites may be and are supplemented by other courses such as atomic theory; electron tubes; advanced differential and integral calculus; etc.

Thus, in our liberalized curriculum, it is not possible for the student to omit any of the basic or fundamental subjects.

It is encouraging to learn that at the University of Pennsylvania there now exists a strong feeling that the standard 4-years' course has become inadequate for the proper training of engineers, and that a longer period is necessary. This, of course, has been our own feeling for some time past.

Professor Brainerd believes that there is a need for unity of action and that little can be expected from the engineering societies. Although, at present, the engineering societies may not give aggressive or formal support to the lengthening of the time of the engineering program, they naturally will encourage any educational development which will produce better trained engineers. As Professor Brainerd implies, the initiative must come from some of the leading engineering schools. If the plan proves successful and the graduates of such schools show themselves to be distinctly superior in the broad as well as in the technical sense, other schools in self defense will feel obliged to follow.

Professor Brainerd's statements concerning education in the 2 older professions, law and medicine, are very pertinent to this subject, and I believe that they may even be prophetic. In the earlier days, the educational methods of training for the profession of the law and of medicine would be considered scandalous according to our present-day educational standards. However, both The Johns Hopkins University under President Gilman and Harvard University under President Eliot assumed leadership in the establishment of graduate schools in these professions. At first, in Harvard at least, there occurred immediately a diminution in the number of students, and this diminution continued for some time. It was some years before it became certain that the plan would succeed. However, the higher standards of these graduate schools began to attract the better students in increasing numbers and this type of education in law and in medicine is now practically universal among the leading universities. Undoubtedly, engineering education will go through a similar development and if the Moore School of Electrical Engineering, with a few others, will have the courage to assume leadership and adopt the graduate plan and demonstrate its effectiveness, the better engineering schools are certain to follow the example.

Incidentally, it has been very interesting to note the reaction which is occurring among our own students. I have always felt that students were unusually keen to appraise general conditions both at their own University and in the outside world. They already realize the importance of a more extended period of engineering training and a very large majority, many with very limited financial resources, are choosing of their own volition the 5-year period leading to the master's degree, in preference to the shorter period in which they are able to obtain their bachelor's degree in engineering in 4 years' time.

I can assure Professor Brainerd that Harvard University is one of the schools that is attempting to "lead them on" and it appears that the University of Pennsylvania is in sympathy with the movement.

May I add that I individually am not responsible for these more recent educational policies at the Harvard Engineering School, which were developed by the engineering faculty as a whole under the leadership of Dean Clifford.

Very truly yours,
C. L. DAWES (M'15)
(Associate Professor of Electrical Engineering, Harvard University, Cambridge, Mass.)

Slide Rule Calculation of Unbalanced 3-Phase Currents

To the Editor:

Consider the 3-phase circuit, Fig. 1, in which the values I_{ab}, I_{bc}, and I_{ac} are unequal and are known by reason of their being single-phase loads which are to be connected to the 3-phase circuit. It is required to find the line currents I_a, I_b, and I_c so as to determine the cable sizes necessary for the installation.

The condition, Fig. 1, may be represented graphically by the vector diagram, Fig. 2, in which

$$I_a = I_{ac} - I_{ab} \quad (1)$$
$$I_b = I_{ab} - I_{bc} \quad (2)$$
$$I_c = I_{bc} - I_{ac} \quad (3)$$

For any values of the currents I_{ac}, I_{ab}, and I_{bc} the angular displacement between them will be such that the point O falls at the center of area of the triangle formed by the currents, I_a, I_b, and I_c. Then from geometry it is known that

$$ON = {}^1/_2\, I_{bc}$$

Therefore

$$I_{ac} + I_{ab} = ON + NM$$

or

$$I_{ac} + I_{ab} = -I_{bc} \quad (4)$$

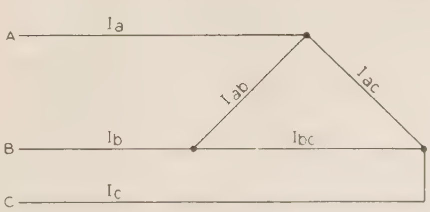


Fig. 1

A mechanical contrivance, as in Fig. 3, can be constructed which will fulfill the condition of eq 4. Four scales, OV, OS, MT, and MW of equal length, and one scale, MX, of double this length are used. Scales MW, MT, and MX are pivoted at M. Scales OV and OS are pivoted at O. Scale MX slides through O. Scales MT and OS are provided with a slide so that point Q can be set anywhere on their length and when once set at this point each of the scales is free to rotate about Q. Point P on MW and OV is similarly adjustable and when set likewise acts as a pivot.

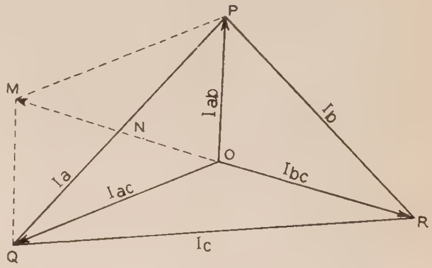


Fig. 2

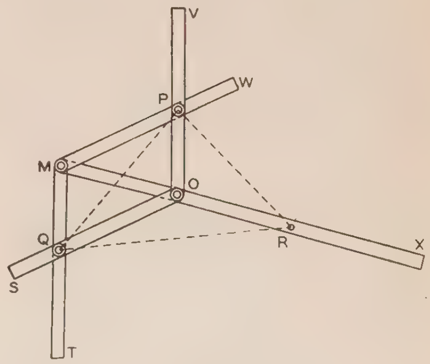


Fig. 3

To arrive at a solution for a certain set of given load currents, I_{ab}, I_{bc}, and I_{ac}, make MP and OQ equal to I_{ac}. Make MQ and OP equal to I_{ab}. Adjust MO until it is equal to I_{bc}. Set length OR equal to MO.

Then from eqs 1, 2, and 3:

$$PQ = I_a$$
$$PR = I_b$$
$$QR = I_c$$

In the solution of problems where the current values as set on the scales would be too small it will be necessary to multiply I_{ab}, I_{bc}, and I_{ac} by the constant K and then to divide the resultants, I_a, I_b, and I_c by K.

Very truly yours,
E. F. SEAMAN
(Assistant Electrical Engineer, Bureau of Engineering, Navy Dept., Washington, D. C.)

Standards

Graphical Symbols Used for Electric Power and Wiring

A new standards pamphlet, No. *17g2*, has just been issued by the Institute covering the accepted American standards for "Graphical Symbols Used for Electric Power and Wiring." This standard, which was developed by the sectional committee on scientific and engineering symbols and abbreviations working under the procedure of the American Standards Association, contains graphical symbols used for one line and complete diagrams of electric power apparatus, instruments, and relays, and maps and connection diagrams. The symbols are limited to apparatus usually encountered in electric power engineering such as major electrical equipment in power houses, substations, transmission and distribution systems and to system wiring diagrams. They are not intended to cover radio, communication, railway or other allied branches of electrical engineering.

Basic symbols which seem to have widespread use and application and only such symbols, with few exceptions, are given. While the symbols presented do not cover all types of equipment, the variations in practice can be accommodated with relatively small additions to the basic symbols. This is especially true of the complete diagram symbols for rotating apparatus and transformers where it is impracticable to show all possible connections of parts. The final approval of this standard was held up for a long period in an effort to eliminate some of the conflicts between symbols it contained and different symbols for the same apparatus as used in the radio and railway fields. This proved impossible. The final standard contains the conflicts but they have been plainly indicated and the symbols involved have not received approval as standards. This standard, No. *17g2* in the A.I.E.E. series, can be obtained by writing H. E. Farrer, A.I.E.E. Headquarters, 33 West 39th St., New York, N. Y. Cost is 20 cents per copy. Usual 50 per cent discount to A.I.E.E. members on single copies.

Graphical Symbols Used in Radio

This new American standard, No. *17g3*, is now available. It also was developed by the sectional committee on scientific and engineering symbols and abbreviations working in close collaboration with the committee on standardization of the Institute of Radio Engineers. It likewise has been held up for the reasons described for *17g2* above and the problem has been solved in the same way. For copies of this standard, No. *17g3*, write H. E. Farrer, A.I.E.E. Headquarters, 33 West 39th St., New York, N. Y. Cost is 20 cents per copy. Usual 50 per cent discount to A.I.E.E. members on single copies.

Graphical Symbols Used for Electric Traction

This new American standard, No. *17g5*, the third in the new graphical symbol series recently approved was developed by the sectional committee on scientific and engineering symbols and abbreviations. It comprises the graphical symbols used for diagrams for electric traction including railway signaling. The symbols are limited to apparatus used in the electrical equipment of power houses, substations, transmission and distribution systems, electrically operated cars and locomotives, and the electrical and associated equipment in railway signaling. The final approval of this standard has been long held up for the reasons outlined in the 2 preceding cases as outlined above. It has been finally approved with the same reservations indicated. Copies of the standard, No. *17g5*, can be obtained by writing H. E. Farrer, A.I.E.E. Headquarters, 33 West 39th St., New York, N. Y. Cost is 40 cents per copy. Usual 50 per cent discount to A.I.E.E. members on single copies.

Two Welding Standards

Two new American standards, Nos. 38 and 39 in the A.I.E.E. series on "Electric Arc Welding Apparatus" and "Electric Resistance Welding Apparatus," respectively are now available. These standards are revisions of the A.I.E.E. standards on the same apparatus. The revisions were developed by the sectional committee on electric welding apparatus working under the sponsorship of the A.I.E.E. and N.E.-M.A. Copies of both pamphlets may be obtained by writing H. E. Farrer, A.I.E.E. Headquarters, 33 West 39th St., New York, N. Y. Cost is, No. 38, 40 cents; No. 39, 30 cents. Usual 50 per cent discount to A.I.E.E. members on single copies.

Constant Current Transformers

A new American standard on "Constant Current Transformers," No. 12 in the A.I.E.E. series, is now available. This is a revision of the A.I.E.E. standard No. 12, which has been available since May 1930. The revision was developed by the electrical machinery committee of the Institute. Copies may be obtained by writing H. E. Farrer, A.I.E.E. Headquarters, 33 West 39th St., New York, N. Y. Cost is 30 cents per copy. Usual discount of 50 per cent to A.I.E.E. members on single copies.

Report on Rotating Electrical Machinery

The first report of the sectional committee on rotating electrical machinery (*C*50), organized in 1930 under the auspices of the American Standards Association has just been published and is now being widely circulated for the purpose of securing comments and suggestions. The report includes standards for d-c rotating machines; synchronous generators, synchronous motors and synchronous machines in general; synchronous converters; induction motors and induction machines in general; and a-c and d-c fractional horsepower motors.

The report is largely based upon the 5 standards of the A.I.E.E. on these same subjects, Nos. 5, 7, 8, 9, and 10. Since the proposed new standards are in the nature of a revision, they will, when approved, supersede these 5 standards. The scope of the standards has been broadened, however, to include, in addition to the material covered in the A.I.E.E. standards, a large number of widely used standard rules developed by the National Electrical Manufacturers Association.

Up to the present time these A.I.E.E. and N.E.M.A. standards have served as the principal bases of specifications for electrical machines. It is expected that the combination of these 2 important sets of standards in a single publication, to be approved finally by the A.S.A., will be of maximum usefulness to the buyer, seller, and manufacturer of rotating electrical machinery.

In the proposed standards emphasis has been placed upon the terms and conditions which characterize the rating and behavior of electrical machinery, with special reference to the conditions upon which acceptance tests are based.

The sectional committee on rotating electrical machinery which is under the sponsorship of the Electrical Standards Committee, is composed of 32 representatives of 15 organizations and is broadly representative of the electrical industry. L. F. Adams, General Electric Co., Schenectady, N. Y., is chairman of the committee.

Comments and suggestions are solicited from all interested in order to assist the committee in satisfactorily rounding the standards into final form. All comments should be addressed to E. B. Paxton, General Electric Co., Schenectady, N. Y.

At the end of a 6 months' period, after criticisms and comments have been received and considered, the standards will be submitted through the sponsor, the Electrical Standards Committee, to the American Standards Association for approval as American standards.

Copies of the report may be purchased from the office of the American Standards Association, 29 West 39th St., New York, N. Y., at 25 cents each.

Standard Methods for Electrical Measurements

The long expected recommended practice on "Electrical Measurements" developed by the A.S.M.E. power test codes committee on instruments and apparatus will become available in March 1934. Throughout the progress of the work on this publication the A.S.M.E. committee had the complete coöperation of the A.I.E.E. standards committee.

Electrical and mechanical apparatus are often closely associated in the generation and use of power. In 1918 when the committee on power test codes of The American Society of Mechanical Engineers outlines the scope of its work, it was natural for it to arrange for the development of supplemen-

tary material on electrical measurements and such a section of "Instruments and Apparatus" was subsequently developed by the P.T.C. Committee No. 19 of which Dr. C. F. Hirshfeld is chairman. Other members of the committee most closely associated with this development are F. Malcolm Farmer and Everett S. Lee.

"Electrical Measurements" contains sections on voltage, current, power, energy, resistance, frequency, and power-factor measurements; instrument transformers, load rheostats, and input of motors and output of generators. The last named section is the one to which the greatest amount of attention was given by the reviewers and the committee feels confident that it now records a definite step in advance. The prepublication price to A.I.E.E. members has been set at $1. Orders with remittance should be sent to publication sales dept., The American Society of Mechanical Engineers, 29 West 39th St., New York, N. Y.

American Engineering Council

Officers Elected at Annual Meeting

J. F. Coleman, consulting engineer of New Orleans, La., past-president of the American Society of Civil Engineers, was elected president and F. M. Feiker, formerly director of the bureau of Foreign and Domestic Commerce of the U.S. Bureau of Commerce, was appointed executive secretary of the American Engineering Council at the annual meeting of American Engineering Council held in Washington, D. C., January 11–13, 1934. Other officers representing the several national and local engineering societies were elected as follows: For vice-presidents of the Council, C. O. Bickelhaupt (M'22, F'26, and past vice-president), vice-president of the American Telephone and Telegraph Company, New York, N. Y., representing the A.I.E.E., Paul Doty (A'04, M'12), consulting engineer, St. Paul, Minn., representing The American Society of Mechanical Engineers, A. J. Hammond, consulting engineer of Chicago, Ill., representing The American Society of Civil Engineers, W. H. Woodbury, Duluth, Minn., representing the local engineering societies. C. E. Stephens (M'22) of the A.I.E.E. was elected treasurer, and William McClellan (A'04, M'09, F'12, and past-president), president of the Potomac Electric Power Company of Washington, was elected chairman of the finance committee.

Retiring president of Council, W. S. Lee (A'04, M'04, F'13) of Charlotte, N. C., in his opening address called attention to the 13 years of development of the American Engineering Council pointing out that to its deeper purpose of serving the public, there had been brought together scores of professional men, leaders in the industrial, engineering, and public utility fields as well as those representing municipal, state, and federal activities. Among those who had been active in Council were 46 presidents of the 4 national societies of civil, electrical, mechanical, and mining engineers, 25 presidents of other national engineering societies, and 69 presidents of state and local professional engineering organizations. Mr. Lee pointed out that nearly $^3/_4$ of a million dollars had been spent to prosecute the public good, through the work of the Council, including some $90,000 for direct research into the engineering values of public and private engineering enterprises.

F. M. Feiker Appointed Executive Secretary

Frederick M. Feiker has been appointed executive secretary of American Engineering Council, Washington, D. C., a position for 13 years held by L. W. Wallace, who has resigned to become vice-president of the W. S. Lee Engineering Corporation. Mr. Feiker brings to his new position a unique experience in both private and public business. Since his graduation as an electrical engineer from Worcester Polytechnic Institute in 1904, he has spent the first half of his business life in editorial and publishing work, having been consecutively editor and chairman of the editorial board of the A. W. Shaw Company of Chicago, Ill., and editor and vice-president in charge of editorial policy for the McGraw-Hill Publishing Company, New York, N. Y.

Beginning in 1920, Mr. Feiker undertook a broader field of public service and was successively assistant to the Secretary of Commerce, operating vice-president of the Society for Electrical Development, managing director of the Associated Business Papers, Inc., director of the Bureau of Foreign and Domestic Commerce of the Department of Commerce. During the past 6 months Mr. Feiker has been in charge of an inquiry into the needs and methods of developing trained men for the textile industry, in coöperation with the textile engineering departments of our northern and southern educational institutions, under an educational grant from the Textile Foundation. Mr. Feiker assumed his new duties early in January.

L. W. Wallace Leaves American Engineering Council

Announcement has been made of the resignation of L. W. Wallace as executive secretary of American Engineering Council, Washington, D. C. Mr. Wallace has been appointed to the position of vice-president of the W. S. Lee Engineering Corporation in charge of the Washington office.

Mr. Wallace has been active in guiding the policies of American Engineering Council since its organization 13 years ago. On February 14, 1921, he was elected executive secretary and held this position continuously up to his recent resignation. Mr. Wallace graduated from Texas Agricultural and Mechanical College with the degree of B.S. in M.E. in 1903, later receiving the degree of M.E. from Purdue University in 1912. From 1903 to 1906 he was special apprentice to the Santa Fe Railway, and between 1906 and 1917 rose from the position of instructor to that of professor at Purdue University. Here he was in charge of the department of railway and industrial management. From 1917 to 1919 he was assistant general manager of the Diamond Chain and Manufacturing Company, Indianapolis, Ind., and from 1919 to 1921 was director of the Red Cross Institute for the Blind, Baltimore, Md. This was followed by his long service with American Engineering Council.

Mr. Wallace is a member of many societies including The American Society of Mechanical Engineers, Washington (D. C.), Society of Engineers, Engineers' Club of Philadelphia, Society of Industrial Engineers (past-president), Indiana Engineering Society (past-president), American Academy of Political and Social Science, Washington Academy of Science, and the American Association for the Advancement of Science. He is an honorary member of the Masaryk Academy of Works, Prague, and the Institute of Scientific Management of Poland. He has been decorated with the Cross of Knight of Order of White Lion (Czechoslovakia).

Engineering Foundation

Valuable Books in Engineering Societies Library

The schedule of books in the Engineering Societies Library located at 33 West 39th Street, New York, N. Y., and upon which the annual appraisal for fire insurance is based for 1934, contains so much of interest about the treasures of this library possessed by the 4 national societies of civil, mechanical, mining, and electrical engineers that a brief note is published herewith.

The appraisal of the books of different classifications is as follows:

General books: 137,250 at $2.50	$343,125
Bibliographies: 1,000 at $1.00	1,000
Catalogs, furniture, etc.	75,000
Rare books and manuscripts:	
Books published between 1501 and 1600, maximum value $100	8,400
Books published between 1601 and 1700, maximum value $75	11,000
Books published between 1701 and 1800, maximum value $50	13,475
Other rare books and manuscripts	28,800
Total	$480,800

Perhaps the most interesting item in this table is "other books and manuscripts," and it is to be regretted that space limitations do not permit further amplification here. Many rare and valuable books and manuscripts are included in this classification. Many of them are old, dating back to 1473 and are of considerable value, the most valuable single item being listed at $3,500. Others, such as an Edison manuscript valued at $1,000, are of comparatively recent origin.

Personal Items

C. W. Kellogg (A'19, M'23) formerly president of the Engineers Public Service Company, New York, N. Y., a subsidiary of Stone and Webster, Inc., has been made chairman of the board of this organization. His connection with the Stone and Webster interests dates back to 1903, following graduation from the Massachusetts Institute of Technology. Since 1925 he has been president of the Engineers Public Service Company.

C. O. Bickelhaupt (M'22, F'28, and past vice-president) vice-president of the American Telephone and Telegraph Company, New York, N. Y., and a representative of the A.I.E.E. on the administrative board of American Engineering Council Assembly, was elected a vice-president of the Council for the 2-year term 1934–35, at its annual meeting held in Washington January 11–13, 1934.

C. E. Stephens (M'22) vice-president of the Westinghouse Electric and Manufacturing Company, New York, N. Y., and a representative of the A.I.E.E. on the administrative board of American Engineering Council Assembly, was elected treasurer of American Engineering Council for the term of 1 year at the meeting held in Washington, D. C., January 11–13, 1934.

William McClellan (A'04, M'09, F'12, and past-president) president of the Potomac Electric Company, Washington, D. C., and a representative of the A.I.E.E. on American Engineering Council Assembly, was elected chairman of the finance committee of American Engineering Council at its meeting held in Washington, D. C., January 11–13, 1934.

W. L. Winter (A'21) sales engineer in the central station department of the San Francisco (Calif.) office of the Westinghouse Electric and Manufacturing Company, has been transferred to the Salt Lake City, Utah, office to succeed the late E. L. Morris. Mr. Winter joined the San Francisco office of the company in 1920.

Paul Doty (A'04, M'12) chairman of the Minnesota State Board of Registration for Architects, Engineers, and Land Surveyors, St. Paul, Minn., and also president of The American Society of Mechanical Engineers, was recently elected a vice-president of American Engineering Council, to serve for the 2-year term 1934–35.

Arnold Roth (A'26) former technical director of the Ateliers de Constructions Electriques de Delle, Villeurbanne, Rhone, France, has recently been entrusted with the direction of the Fabrique d'Appareillage Electrique Sprecher & Schuh, Aarau, Switzerland.

J. A. Walls (A'03, F'13) vice-president and chief engineer of the Pennsylvania Water and Power Company, Baltimore, Md., since 1914, and of the Safe Harbor Water Power Corporation since its founding, has been elected president of both of these organizations.

F. A. Allner (A'12, M'14) general superintendent of the Pennsylvania Water and Power Company, Baltimore, Md., was recently elected a vice-president of that company. Mr. Allner has been associated with the Pennsylvania Water and Power Company since its organization in 1910.

Melville Eastham (A'19, M'26) president of the General Radio Company, Cambridge, Mass., has been appointed a member of the board of directors of the Institute of Radio Engineers for the year 1934.

W. G. Cady (M'19) professor of physics, Wesleyan University, Middletown, Conn., and junior past-president of the Institute of Radio Engineers, continues as a member of the board of directors of this organization during 1934.

William Wilson (M'23) assistant director of research, Bell Telephone Laboratories, Inc., New York, N. Y., has been elected a member of the board of directors of the Institute of Radio Engineers for the years 1934–36.

E. L. Nelson (A'20, M'26) radio development engineer, Bell Telephone Laboratories, Inc., New York, N. Y., continues as a member of the board of directors of the Institute of Radio Engineers for the year 1934.

E. R. Shute (M'17) general superintendent of traffic, Western Union Telegraph Company, New York, N. Y., has been appointed a member of the board of directors of the Institute of Radio Engineers for the year 1934.

J. V. L. Hogan (A'11, M'20) consulting engineer, New York, N. Y., has been appointed a member of the board of directors of the Institute of Radio Engineers for the year 1934.

A. N. Goldsmith (M'15, F'20, and life member) editor of the Institute of Radio Engineers, has been elected a member of the board of directors of this organization to serve for the 3-year term 1934–36.

L. M. Hull (M'27) Aircraft Radio, Boonton, N. J., and junior past-president of the Institute of Radio Engineers, becomes a member of the board of directors of this organization for the 2-year term 1934–35.

O. H. Caldwell (A'13, M'22) editor of *Electronics*, New York, N. Y., continues as a member of the board of directors of the Institute of Radio Engineers for the year 1934.

R. A. Heising (A'15) radio engineer, Bell Telephone Laboratories, Inc., New York, N. Y., continues as a member of the board of directors of the Institute of Radio Engineers during the years 1934–35.

L. C. F. Horle (A'20, M'22) consulting engineer, Newark, N. J., has been appointed a member of the board of directors of the Institute of Radio Engineers for the year 1934.

F. A. Kolster (M'19) International Communications, Inc., New York, N. Y., continues as a member of the board of directors of the Institute of Radio Engineers for the years 1934–35.

H. M. Turner (A'20) associate professor of electrical engineering, Yale University, New Haven, Conn., continues as a member of the board of directors of the Institue of Radio Engineers for the years 1934–35.

C. T. Mess (A'27, M'29) assistant engineer of the California State Railroad Commission, has been appointed valuation engineer of that organization.

C. M. Jansky, Jr. (A'20, M'32) consulting radio engineer, Washington, D. C., has been elected president of the Institute of Radio Engineers for the year 1934.

Obituary

Giuseppe Faccioli (A'04 M'11, F'12, and past vice-president) former works engineer and associate manager of the Pittsfield, Mass., works of the General Electric Company, died in Pittsfield, Mass., January 13, 1934. He was born at Milan, Italy, in 1877. In 1899 he graduated from the University of Milano, as a mechanical and electrical engineer, obtaining the gold medal assigned by the Society of Italian Engineers for the highest scholarship. For the following year he was with the Societa Elvetica of Milano, manufacturers of locomotives, engaged in changing the motive power of the factory from steam to electricity. From 1900 to 1901 he was with the Tecnomasio Brown Boveri Company of Milano, being at first in the testing room and later in charge of the design of induction motors and alternators. From 1901 to 1902 he engaged as a consulting engineer. In 1902 he came to the United States, being in the testing laboratory of the New York Edison Company for the first few months. During the year 1903 he was with the Interborough Rapid Transit Company, New York, in L. B. Stilwell's office as inspector in the installation of the lighting system in the New York subway. During 1904 he was with the Crocker-Wheeler Company as designing engineer, mainly assisting William Stanley in the development of his new type of induction alternator. Early in 1905 he became assistant

to Mr. Stanley in his Great Barrington, Mass., laboratory, engaged in the development of several types of equipment. In 1906, with Mr. Stanley, he entered the employ of the General Electric Company, continuing work at the Great Barrington laboratory until 1908 when Mr. Faccioli was transferred to the railway department at Schenectady, N. Y. Later the same year he was transferred to the transformer department as advisory engineer, and in 1911 was appointed assistant engineer of the transformer department. Later he was transferred to the Pittsfield works, and in 1913 was appointed works engineer of the Pittsfield plant. In 1927 he became associate manager. He retired because of ill health in 1930. The Institute's Lamme Gold Medal for 1931 was presented Mr. Faccioli during the summer convention at Cleveland, Ohio, in 1932, "for his contributions to the development and standardization of high-voltage oil-filled bushings, capacitors, lightning arrestors, and numerous other features in high voltage transformers and power transmission." Mr. Faccioli had served the Institute as manager 1918–22, and as vice-president 1922–24. He also had served on the following committees of the Institute: board's committee on technical activities 1919–20, Edison Medal 1919–21 and 1922–24, electrical machinery 1919–27, electrophysics 1916–17, protective devices 1916–17, transmission and distribution 1918–19, and code of principles of professional conduct 1921–34. Mr. Faccioli was the author of many papers on engineering subjects.

Everett Morss (A'11, M'11, F'13) president of the Simplex Wire and Cable Company, Boston, Mass., died in that city December 27, 1933. He was born in Boston in 1865. In 1885 he received the degree of bachelor of science from Massachusetts Institute of Technology, Cambridge, and in that year undertook to manufacture insulated wire for the predecessor of The Simplex Electrical Company; after nearly a year of experimenting he developed the Simplex T. Z. R. weatherproof wire. In 1889 he started the manufacture of rubber insulated wire, the business gradually developing into the manufacture of all varieties of rubber insulated wire and cable. In 1895, upon the incorporation of The Simplex Electrical Company, Mr. Morss became its vice-president, and in 1903 became president. Throughout the history of The Simplex Electrical Company and its predecessors, he had charge of the manufacture, including the development of all processes, building of factories, and all technical and engineering problems. In 1895 he took charge of the manufacture of electric heating apparatus for the American Electric Heating Corporation, but after 2 or 3 years was obliged to give up direct charge of this work because of insufficient time to devote to it. In 1902 he became vice-president of the Simplex Electric Heating Company, upon its incorporation, and for a number of years he had much to do with the development and manufacture of its products, although not actively in personal charge. Upon the incorporation of the Simplex Wire and Cable Company, Mr. Morss became president, continuing in this capacity until his death. He also was president of the Franklin Foundation, and was a trustee and director in several concerns. During the War he was a member of the priorities committee of the War Industries Board 1917–18, and chief of its brass section 1918. He was a member of the corporation of Massachusetts Institute of Technology, having served as treasurer and a member of the executive committee, and has been president of the Boston Chamber of Commerce 1921. He was a member of The American Society of Mechanical Engineers and of Theta Zi fraternity. In 1923 Tufts College conferred upon him the degree of master of arts. He was a member of the following clubs: Metropolitan (Washington); Union, University, Exchange, St. Botolph, Algonquin (Boston); Engineers', Bankers (New York); and Country (Brookline).

William Bancroft Potter (A'96, M'96) formerly consulting engineer of the transportation department of the General Electric Company, Schenectady, N. Y., and for many years the engineer of the company's railway department, died January 15, 1934. He was born in 1863 at Thomaston, Conn. From 1881 to 1887 he was a machinist for E. H. Judd and Son, Hartford, Conn. From 1887 he became engineer for the Thomson-Houston Electric Company, Lynn, Mass. In 1894 he was transferred to Schenectady, being chief engineer of the railway department of the General Electric Company between 1895 and 1930. In the latter year he retired from active service. During the early years of his career he devised the series-parallel controller for street cars, which for many years has been the underlying principle of most methods of street car control systems. He also was active in the promotion of gas-electric rail cars and oil-electric locomotives, and directed several railroad electrifications. Some 134 patents had been granted him. He has written many articles for technical societies and was a member of the American Society of Civil Engineers, The American Society of Mechanical Engineers, and the Society of Naval Architects and Marine Engineers. He was a member of the following clubs: Engineers', Transportation, Railroad (New York); Mohawk, Mohawk Golf, Edison (Schenectady); and Griswold (Erie). For the Institute, Mr. Potter served as a member of the traction and transportation committee 1916–17, 1919–21, and 1923–24; transportation committee 1925–32; and education committee 1933–34.

Joseph Dufferin Peters (M'25) general manager and engineer for the National Light and Power Company, Moose Jaw, Saskatchewan, Canada, died November 27, 1933. He was born in Perth County Ontario, in 1884. He studied for 2 years at the Collegiate Institute, Stratford, Ontario. Up to 1907 he was engaged in the operation and construction of steam plants and distribution systems for the following organizations: Thames Dairy Company, London, Ontario; Canadian Milk Products Company, Brownsville, Ontario; Barkey Bros., Tillonsburg, Ontario; and London Electric Company, now Ontario Hydro Electric Power Commission, London, Ontario. From 1907 to 1908 he installed the electric plant for the Moore Milling and Electric Company, Qu'Appelle, Saskatchewan. From 1908 to 1909, he was operating engineer of the Municipal power plant at Moose Jaw. In the latter year he became manager of the municipal light and power department for the city and Moose Jaw, remaining in this capacity until 1930; here he designed and redesigned equipment and supervised construction and operation of the system during its development from 600-kw to 11,000-kw capacity. From 1930 until his death he was general manager for the National Light and Power Company, Ltd., purchasers of the Moose Jaw plant. During this period he supervised further additions to the plant to a total capacity of 21,000 kw. He had served the Institute as a chairman of the Saskatchewan Section. Mr. Peters also was a member of the Registered Professional Engineers' Society, Province of Saskatchewan, and was an associate member of the Engineering Institute of Canada, having been chairman of its Saskatchewan Branch.

Arthur A. Brown (A'10, M'13) assistant to vice-president, Westinghouse Electric and Manufacturing Company, New York, N. Y., died December 19, 1933. He was born at Three Creeks, Ark., in 1873. After serving as an apprentice in the foundry and machine shop of the H. B. Smith Company, Westfield, Mass., he entered the mechanical engineering department of the University of Illinois in 1898. At the end of 3 years he went to work with the Bethlehem Steel Company, South Bethlehem, Pa., as machinist. A few years later he returned to the H. B. Smith Company as assistant superintendent, 2 years later becoming general superintendent of the Richmond Company of Norwich, Conn., manufacturers of house heating apparatus. A short time later he became general manager of the Rarig Engineering Company of Columbus, Ohio, manufacturers of blowing engines and blasting furnaces. In 1904 he gave up industrial work and entered the sales department of the Westinghouse Machine Company, Pittsburgh, Pa. In 1907 he was made Pittsburgh district manager for the Westinghouse-Church-Kerr Company. Two years later he was placed in charge of all syndicate operations of the Westinghouse Electric and Manufacturing Company, with headquarters in New York, holding this position continuously from 1909 to 1926, when he was appointed assistant to vice-president. He was a member of the former National Electric Light Association, and the Engineers' Club, The Railroad Club, and the Bankers' Club, all of New York, and Siwanoy Country Club.

Clare Nowlen Stannard (A'28) vice-president and general manager of the Public Service Company of Colorado, Denver, and one of the most prominent executives in the Henry L. Doherty organization, died in Denver on January 2, 1934, after a short illness. Born in Friendship, N. Y., in 1869, he attended public and high schools in Binghamton, N. Y., then obtained training for special work in 7 years as a cadet with the Binghamton Gas and Electric Company, including training in banking, street railway,

gas, electric, and water utility work. In 1897 he entered the employ of the Denver Tramway Company, transferring to the Denver Consolidated Electric Company in 1898. This company was merged to form the Denver Gas and Electric Light Company, and later the Public Service Company of Colorado. Mr. Stannard became commercial manager of the company, and in 1921 was made vice-president and general manager and was active in this office until his death. During his administration the company developed rapidly and extended its services to cover a large portion of the state. He was prominent in the civic activities of his city and state, and was a member of many clubs and organizations, including the Denver Club, Rotary, Denver Country Club, Denver Athletic Club, Cherry Hills Club, Wigwam Club, Illuminating Engineering Society, and was past vice-president of the American Gas Association and past president of the National Commercial Gas Association. He also had served as president of the Rocky Mountain division of the National Electric Light Association.

Membership

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before January 31, 1934, or March 31, 1934, if the applicant resides outside of the United States or Canada.

Aggers, C. V., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Armstrong, G. C. (Member), Westinghouse Elec. Mfg. Co., E. Pittsburgh, Pa.
Aycock, W. C., N. Y. & Queens Elec. Lt. & Pwr. Co., Flushing, L. I., N. Y.
Bayer, M. H., East End Music Co., N. Y. City.
Bond, E. Jr., Union Carbide Co., Niagara Falls, N. Y.
Bozak, E. M., C. J. Crowley Elec. Co., Torrington, Conn.
Brabson, R. M., Jr., N. Y. & Queens Elec. Lt. & Pwr. Co., Flushing, L. I., N. Y.
Brooks, W. W., Ill. Water Survey, Mason City.
Brunn, R. B. J., Savil Radio Engr. Corp., N. Y. City.
Brunner, C., Metropolitan Device Corp., Bklyn., N. Y.
Burke, T. A., N. Y. State Dept. of Health, Albany, N. Y.
Burton, W. R., Ohio Bell Tel. Co., Cleveland.
Campbell, D. L., Okla. Gas & Elec. Co., Sapulpa.
Canepa, T. T., 1415 No. Bdway., Milwaukee, Wis.
Carson, R. J., Bklyn. Edison Co., Inc., Bklyn., N. Y.
Clark, H. W. (Member), Potomac Elec. Pwr. Co., Washington, D. C.
Cluver, H. J., 161 W. 100 St., N. Y. City.
Cottony, H. V., 317 W. 124 St., N. Y. City.
Cowan, J., Bronx Gas & Elec. Co., N. Y. City.
Davis, A. F., 123 W. Houston St., Tyler, Texas.
Dewey, C. S., Natl. Equip. Co., Springfield, Mass.
Driver, P. C., 1607 Opal St., Pullman, Wash.
Dunn, A., 470 Ontario St., Albany, N. Y.
Edwards, L. T., Main St., East Hampton, L. I., N. Y.
Eldred, W. N., 527 Almer Rd., Burlingame, Calif.
Emery, G. W. (Member), The Froehlich & Emery Engg. Co., Toledo, O.
Emery, J. R., (Member), The Froehlich & Emery Engg. Co., Toledo, O.
Ensmann, B., N. Y. Edison Co., N. Y. City.
Ensor, A. H., 14 Tilton Ave., Brockton, Mass.
Farber, L. M., Fisher Body Corp., Leeds, Kansas City, Mo.
Finkenauer, F. J., Jr., c/o Samuel Bell, Jr., Inc., Germantown, Phila., Pa.
Fleshler, A. D., Transit Commission, N. Y. City.
Gabalis, C. A., N. Y. Edison Co., N. Y. City.
Gabel, G. H., Pa. Dept. of Highways, Selinsgrove.
Gagnier, C. E., Carnegie Steel Co., Youngstown, O.
Goodsell, E. M., Meriam Co., Cleveland, O.
Gordon, G. (Member), 31 So. Miller St., Newburgh, N. Y.
Grauch, W. F., Pa. Dept. of Highways, Upper Darby.
Green, H. A., The Green-Mills Const. Co., Bedford, O.
Grossfeld, C., 1634 80th St., Bklyn., N. Y.
Guinther, G. LaV., Defiance Paper Co., Niagara Falls, N. Y.
Halamka, G. L., 1419 Douglas Ave., Racine, Wis.
Harmon, E. B., Mountain States Tel. & Tel. Co., Denver, Colo.
Harries, K. R., Potomac Elec. Pwr. Co., Washington, D. C.
Hart, N. L., 10275 Pico Blvd., Los Angeles, Calif.
Hoff, H. B., Am. Dist. Tel. Co., Cleveland, O.
Hoffman, K. B., N. Y. Edison Co., N. Y. City.
Hostetter, J. W., N. Y. Edison Co., N. Y. City.
Hulswit, W. H., Jr., Northwestern Univ., Evanston, Ill.
Inskip, L. S., Am. Tel. & Tel. Co., N. Y. City.
Job, B. W., 2634 South Troy St., Chicago, Ill.
Kazine, I. A., 46 Downing St., Bklyn., N. Y.
Kennedy, H. E., 105 Tunnel Rd., Berkeley, Calif.
Kime, R. M., N. Y. Edison Co., N. Y. City.
Kinzelman, G. W., 6553 Newgard Ave., Chicago, Ill.
Kisch, J. P., Pub. Serv. Elec. & Gas. Co., Irvington, N. J.
Kloeblen, E. M., J. G. White Engg. Corp., N. Y. City.
Knight, K. T., Carolina Pwr. & Lt. Co., Marion, S. C.
Kopper, J. M., The Garey School, Aberdeen, Md.
Kuelthau, W. A., Pub. Serv. Commission of Wis., Madison.
Kuyper, W. W., Gen. Elec. Co., Schenectady, N. Y.
Larson, S. D., 614 E. St. Vrain St., Colo. Springs, Colo.
Lattin, W. J., Columbia Univ., Univ. Heights, N. Y. City.
Lindemuth, H. F., N. Y. Edison Co., N. Y. City.
Loustaunau, J. J., 216 W. Johnson St., San Antonio, Texas.
Lovelace, C. K., Okla. Gas & Elec. Co., Enid.
Lowe, R. E., Gen. Elec. Co., N. Y. City.
Marceau, J. P., 5073 Bourbonniere Ave., Montreal, Quebec, Can.
Meador, J. R., Gen. Elec. Co., Pittsfield, Mass.
Montgomery, W. N. (Member), Missouri Chiropractic Col., St. Louis, Mo.
Mulholland, R. A., East 3rd St., Lampasas, Texas.
Murphy, L. W., 12 Stedman St., Hartford, Conn.
Nalder, P. R., U. S. Bureau of Reclamation, Almira, Wash.
Newman, W. W., Great Falls, S. C.
Olsen, M. L., Southwestern Bell Tel. Co., Okla. City, Okla.
Parks, C. E., Jr., Northern Ind. Pwr. Co., Kokomo, Ind.
Payne, W. T., Y.M.C.A., Springfield, Mass.
Persio, L. N., 224 W. 4 St., Williamsport, Pa.
Philipps, R. J., Kenyon Transformer Co., Inc., Bronx, N. Y. City.
Poliseo, J., 423 Chadwick Ave., Newark, N. J.
Potter, F. M., Worcester Poly. Inst., Mass.
Powell, J. R., Jones & Laughlin Steel Corp., Aliquippa, Pa.
Queen, H. J., 106 Utica Ave., Bklyn., N. Y.
Reid, J. O., United Elec. Lt. & Pwr. Co., N. Y. City.
Reid, W. S., Potomac Elec. Pwr. Co., Washington, D. C.
Richards, H. N., Pa. Elec. Repair Co., Pittsburgh.
Schulz, E. L., N. Y. & Queens Elec. Lt. & Pwr. Co., Flushing, N. Y.
Seidman, S. M., Ohio Bell Tel. Co., Cleveland.
Shaw, F. W., Kansas City Pwr. & Lt. Co., Mo.
Siedler, F., Pa. R.R., Phila.
Slinger, R. N., Gen. Elec. Co., Schenectady, N. Y.
Smith, W. H., 124 W. Glenarm St., Pasadena, Calif.
Smith, W. S., S. C. State Highway Dept., Kershaw, S. C.
Spielman, S. C., Philco Radio Co., Phila., Pa.
States, F. P., Emakr Battery Corp., Belleville Pike, Kearny, N. J.
Stringer, G. L., 26 Middagh St., Bklyn., N. Y.
Thompson, A. I., 62 Summit St., Ridgefield Park, N. J.
Titgemeyer, J. C. (Member), The Froehlich & Emery Engg. Co., Toledo, O.
Toole, M. G., Clark St., Maryville, Tenn.
Toombs, J. E., 224 W. Centennial Ave., Muncie, Ind.
Triest, R. M., John Wiley & Sons, N. Y. City.
Tutwiler, J. W., N. & W. Ry., Portsmouth, O.
Urquhart, A. R., Broad River Pwr. Co., Columbia, S. C.
Wells, E. R., Ohio Pwr. Co., Newark.
White, J. L. (Member), Appalachian Electric Pwr. Co., Roanoke, Va.
Young, R. Z., Pacific Tel. & Tel. Co., San Francisco, Calif.
Young, S. G., Averill Park, N. Y.
Zittel, T. O., Civil Works Assn., Buffalo, N. Y.

108 Domestic

Foreign

Ducati, A. C., Societa Scientifica Radio, Bologna, Italy.
Golding, E. W. (Member), Univ. Col., Nottingham, Eng.
Guha, S. K., Pub. Works Dept., Burma, India.
Hahlbeck, H. A., United River Plate Tel. Co., Buenos Aires, Argentina.
Hamid, A., Pub. Works Dept., Batala, Dist. Gurdaspur, Punjab, India.
Jan, S. K., Kashmir Hydro Elec. Installation, Baramulla, Kashmir, India.
Romanovsky, V. B., Electroapparat, W. O. 24 Linia, Leningrad, U. S. S. R.
Stanbridge, C. H. (Member), P. O. Box 1230, Cape Town, South Africa.

8 Foreign

Recommended for Transfer

The board of examiners, at its meeting of January 17, 1934, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Clarkson, Albert J., supt. of electric equipment, N.Y.C. R.R. Co., Harmon-on-Hudson, N. Y.
Davis, Ernest W., Chief E.E., Simplex Wire & Cable Co., Cambridge, Mass.

To Grade of Member

Breece, Charles A., commercial survey engr., Indiana Bell Tel. Co., Indianapolis.
Burbank, Jerome, elec. and radio engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Coolidge, Wm. D., director of research lab., Gen. Elec. Co., Schenectady, N. Y.
Davidson, Roy J., asst. chief engr., Pacific Pwr. & Lt. Co., Portland, Ore.
Everson, Walter A., pres., Everson-Leidy Elec. Co., Allentown, Pa.
Fairburn, A. J. B., instructor in E.E., Cooper Union Inst. of Tech., New York.
Fuhs, Raymond H., transformer engr., Indianapolis Pwr. & Lt. Co., Ind.
Kitchen, W. A., asst. supt. of elec. dept., Oklahoma Gas & Elec. Co., Oklahoma City.
Kummer, Ludwig, acting chief engr., Trinidad Leaseholds, Ltd., Pointe-a-Pierre, Trinidad, B. W. I.
Pilkington, John H., division engr., Bklyn. Edison Co. Inc., Bklyn., N. Y.
Ralston, Emmet G., operating vice-pres., Indianapolis Pwr. & Lt. Co., Ind.
Schleicher, George B., technical asst., meter div., Phila. Elec. Co., Pa.
Sullivan, George L., asst. engr., Bklyn. Edison Co Bklyn., N. Y.
Tasker, Homer G., chief engr., United Research Corp., Long Island City, N. Y.
Van Why, Forbes, W., control and transmission engr., KMTR Radio Corp., Hollywood, Calif.
Watts, Thomas R., research engr., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Woltz, Fred I., manager, industrial pwr. serv., Metropolitan Edison Co., Easton, Pa.
Zimmerman, Andrew G., technical man, The Pacific Tel. & Tel. Co., San Francisco, Calif.

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Blackhall, Harold J., Postlagernd, Essen, Germany.
Bugnion, Frank E., 14 Clinton St., Cambridge, Mass.
Code, F. L., 6061 Trafalgar St., Vancouver, B. C., Can.
Darcy, Harris B., 305 M. & M. Bldg., Houston, Texas.
Dean, George H., Corrie, Old Shoreham Road, Shoreham-by-Sea, Eng.
Gentilini, Celso, 1512 Wood St., Wilkinsburg, Pa.
Griffith, Geo. M., R. no. 1, Tucker, Ga.
How, John H., 42 Wai Oi Road East, Canton, China.
Kahale, N. A., Box 434, W. Lafayette, Ind.
Lober, Charles, K. C. P. & L. Co., 1330 Baltimore Ave., Kansas City, Mo.
Mathisen, Karsten, V., 912 Noyes St., Evanston, Ill.
Panton, H. D., Phoenix Utility Co., c/o Kansas Gas & Elec. Co., Wichita, Kans.
Shifrin, Leonard I., c/o Tanenbaum, 12 Pinehurst Ave., New York City.
Soskin, Samuel B., 1225 S. Calif. Ave., Chicago, Ill.
Sparks, Losey D., 1507 Sherwin Ave., Chicago, Ill.
Talbot, H. L., 55 Pine Ave. E., Montreal, Que., Can.
Weber, George A., 537 Addison Ave., Palo Alto, Calif.
Whittemore, J. D., 126 State St., Albany, N. Y.

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, during December are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

FORSCHUNGSHEFT 362. KURZSCHLUSSERWÄRMUNG von KABELN. By A. Hecht. Berlin, VDI-Verlag, 1933. 25 p., illus., 12 x 8 in., paper, 5 rm. This, according to the author, is the first study to be made of the heating of insulated cables during short circuits. The question is here subjected to a theoretical and experimental investigation. Formulas for practical use are developed.

HANDBOOK of CHEMISTRY and PHYSICS, 18 ed. Edit. by C. D. Hodgman. Cleveland, Ohio, Chem. Rubber Pub. Co., 1933. 1818 p., illus., 7 x 4 in., lea., $6.00. Intended to provide the physical and chemical tables and formulas needed by engineers and scientists. This edition has been thoroughly revised and enlarged by the addition of numerous new tables and the extension of former ones.

INTRODUCTION to THEORETICAL PHYSICS. By J. C. Slater and N. H. Frank. N. Y. and Lond., McGraw-Hill Book Co., 1933. 576 p., illus., 9 x 6 in., cloth, $5.00. Presents the classical and the more modern parts of theoretical physics as a coherent whole. Intended to familiarize the reader with the methods and principles of the subject, and enable him to read advanced books on its various branches. A knowledge of descriptive physics and of mathematics through the calculus is assumed.

(The) INVENTOR and HIS WORLD. By H. S. Hatfield. N. Y., E. P. Dutton & Co., 1933. 269 p., diagrs., 8 x 5 in., cloth, $2.40. Indicate the temperament characteristic of the inventor, shows how he works, explains why it is so difficult for him to get his invention adopted, and indicates promising directions for his efforts. Mechanical, chemical, electrical, biological, and psychological inventions are discussed quite fully, and the workings of patent law are considered.

McDONALD'S ELECTRICAL DICTIONARY. By G. McDonald. Boston, Meador Pub. Co.. 1933. 178 p., 8 x 5 in., lea., $1.50. Over 2,000 electrical terms are defined. The definitions are simple and, in most cases, clear, and cover adequately the ordinary needs of the student of electricity.

PRACTICAL ACOUSTICS for the CONSTRUCTOR. By C. W. Glover. Lond., Chapman & Hall, 1933. 468 p., illus., 9 x 6 in., cloth, 25s. For the architect or engineer in search of practical information. The theory of acoustics is presented clearly and its application to the design of buildings illustrated. Sound insulation, noise, and vibration reduction, the use of sound absorbents, and aircraft noise are discussed. Typical specifications for acoustical work are given. Appendixes include a useful bibliography, tables of acoustical coefficients for 700 materials, and particulars of many representative materials for damping sound and vibration.

Les REDRESSEURS de COURANT, Construction, Caractéristiques, Utilisation des Valves Électriques. By R. de Bagneux. Paris, Étienne Chiron, 1933. 124 p., illus., 9 x 6 in., paper, 10 frs. The principles, properties, and uses of the various types of rectifiers are presented in a practical, nonmathematical fashion in this book, intended for amateur radio operators and electrical workers. Special attention is given to questions of maintenance.

RÉSEAUX de DISTRIBUTION d'ÉNERGIE ÉLECTRIQUE. (Memento d'Électrotechnique, v. 3). By A. Curchod. Paris, Dunod, 1934. 655 p., illus., 8 x 5 in., cloth, 138 frs. A comprehensive, concise reference work to which the electrical engineer may turn for definite information upon current practice. The present volume is devoted to the production, transformation, transmission, and distribution of electricity. French legislation affecting the distribution of electricity is included.

THEORIE der ELEKTRIZITÄT Bd. 2, ELEKTRONENTHEORIE. By R. Becker. 6 ed. Leipzig and Berlin, B. G. Teubner, 1933. 400 p., illus., 9 x 6 in., cloth, 17 rm. This, the second volume of a thorough revision of Max Abraham's text on the theory of electricity, discusses the electron. While based upon the classic theory of the electron, the text also considers it from the viewpoint of the quantum theory. In addition to general principles, the volume discusses the elastically constrained electron, field equations in static and moving media, the electronic theory of metals and the theory of radiation in empty space.

(The) THEORY of ATOMIC COLLISIONS. By N. F. Mott and H. S. W. Massey. Oxford (Eng.), Clarendon Press; New York, Oxford University Press, 1933. 283 p., illus., 10 x 6 in., cloth, $6.00. The sixth volume of the international series of monographs on physics. Develops the quantum mechanical theory of collisions between electrons, alpha particles, nuclei, and atomic systems generally. The complete theory is given and the way is shown to draw many important deductions about the properties and structure of the nucleus. Special attention is paid to collisions between particles moving with relatively small velocities.

THEORY of FUNCTIONS as Applied to Engineering Problems. Edit. by R. Rothe, F. Ollendorff and K. Pohlhausen, authorized translation by Alfred Herzenberg. Cambridge, Technology Press, Massachusetts Institute of Technology, 1933. 189 p., illus., 10 x 6 in., cloth, $3.50. Based upon a series of lectures. The first half of the volume deals with the theory from the point of view of pure mathematics and gives a general knowledge of the methods of function theory. The second part consists of 5 lectures upon specific applications, chiefly to problems of electrical engineering; the construction of electric and magnetic fields by means of source-line potentials; 2-dimensional fields of flow; the field distribution in the neighborhood of edges; the complex treatment of electric and thermal transient phenomena; and the spreading of electric waves along the earth.

THOMAS ALVA EDISON, the Youth and His Times. By W. E. Wise. Chicago, N. Y., San Francisco, Rand McNally & Co., 1933. 252 p., illus., 8 x 6 in., cloth, $2.00. The story of Edison's youth, ending with the sale of his stock ticker, at the age of 23. The author has collected many stories of Edison's life as a train boy and telegrapher, which he weaves into an interesting record that will appeal to boys. There is a bibliography.

UNTERNEHMUNGSFORM und VERKAUFSPOLITIK der STROMVERSORGUNG. By H. Kirchhoff. Berlin, Julius Springer, 1933. 188 p., tables, 10 x 9 in., paper, 8 rm. A critical study of electrical public utilities in Germany, with emphasis upon problems of organization and tariffs. The economic effects of public and private ownership upon the production of electricity are considered at length, and the relations between tariffs, costs, and consumption discussed.

Die WIRTSCHAFTLICHKEIT der FERNSPRECHANLAGEN. By F. Lubberger. 2 ed. Munich and Berlin, R. Oldenbourg, 1933. 124 p., illus., 10 x 7 in., paper, 6.80 rm. Because the operating data of the 1927 edition of this study of telephone economics are out of date, a new edition has been prepared, based upon current figures. At the same time scope of the work has been enlarged to include long-distance and automatic telephony.

BAIRD of TELEVISION, the Life Story of John Logie Baird. By R. F. Tiltman. London, Seeley Service & Co., Ltd., 1933. 220 p., illus., 9 x 6 in., cloth, 10s 6d. This biography includes the early struggles and the achievements of Baird, written in an easy style, emphasis being upon the inventor's life, not upon the technicalities of his invention.

Der SELEKTIVSCHUTZ nach dem WIDERSTANDSPRINZIP. By M. Walter. Munich and Berlin, R. Oldenbourg, 1933. 172 p., illus., 10 x 7 in., paper, 8.50 rm. A comprehensive, systematic presentation of the subject of selective relaying on the resistance principle, intended for practicing engineers as well as students. The method of operation and the planning of typical systems of protection are presented simply and practically.

WORLD RESOURCES and INDUSTRIES. By E. W. Zimmermann. N. Y. and Lond., Harper Bros., 1933. 842 p., illus., 10 x 6 in., cloth, $5.00. An important, timely appraisal of world resources. The agricultural and industrial resources of the world are reviewed, stress being laid upon their relativity and functional nature. Future prospects are discussed. The book has much of interest to economists, manufacturers, and business men.

CHEMICAL PATENT INDEX, [United States] 1915–1924. Vol. 3, Subject Index F-L. By E. C. Worden, N. Y., Chem. Cat. Co., 1933. 1004 p., 10 x 7 in., cloth, $25.00. Covers the entire field of chemical technology and that of chemical development. Over 22,000 patents issued in the decade 1915–1924 are indexed under patentees and under all possible subjects. Volume 3 comprises letters F to L of the subject index. It contains approximately 160,000 subject entries.

CRYSTALLINE STRUCTURE in relation to FAILURE of METALS, especially by Fatigue. (Edgar Marburg Lecture 1933.) By H. J. Gough. Phila., Am. Soc. for Testing Materials, 1933. 111 p., illus., 9 x 6 in., paper, $1.00. Discusses the knowledge of deformation and fracture under mechanical forces which has resulted from extensive studies of single metallic crystals. The lecture summarizes in an effective way what is known of the nature of solid bodies. It should interest chemists and physicists, as well as engineers and metallurgists.

Die DREHZAHLREGELUNG von ASYNCHRONMOTOREN durch WECHSELSTROMKOMMUTATORHINTERMASCHINEN. By H. Zabransky. Berlin, Carl Heymanns Verlag, 1934. 208 p., diagrs., 10 x 7 in., paper, 16 rm. An exhaustive account of the use of a-c commutator machines to control the speed of induction motors. The material is classified by purposes and is complete to the end of July 1933. Patent numbers are given throughout, and a subject index is provided.

GEOLOGY of CALIFORNIA. By R. D. Reed. Tulsa, Okla., Am. Assn. of Petroleum Geologists, 1933. 335 p., illus., 9 x 6 in., cloth, $5.00. A sketch of the stratigraphy, structure, and geologic history of California, with particular reference to post-Triassic events in the coastal province. Brings into relief some of the major unsolved problems of California geology; and furnishes geologists in general with an introductory account of the present status of geologic work in this state.

INTERNATIONAL ACETYLENE ASSOCIATION PROCEEDINGS, 33rd Annual Convention, 1932. N. Y., The Assn., 1933. 201 p., 9 x 6 in., cloth, not for sale. The papers presented deal with the uses of oxy-acetylene cutting and welding processes. The use of welded piping in power plants and residences, welding in the aircraft industry and in railroad and truck maintenance, weld testing, etc., are discussed. The reports of the Association and a list of its members are also included.

MITTEILUNGEN des HYDRAULISCHEN INSTITUTS der TECHNISCHEN HOCHSCHULE MÜNCHEN. Heft 7, 1933. By D. Thoma. Munich and Berlin, R. Oldenbourg. 86 p., illus., 11 x 8 in., paper, 5.80 rm. Contains 4 papers. The first describes investigations of the lubricating capacity of oils and fats. The second treats of flow over weirs. The effects of sudden stoppage upon turbine pumping plants are discussed in the third paper, based upon experiments with large and small pumps. The final paper describes a new hot-wire instrument for determining the direction and magnitude of the velocity of turbulent water.

THEORETICAL PHYSICS. Vol. 2, Electromagnetism and Optics. Maxwell-Lorentz. By W. Wilson. Lond., Methuen & Co.; N. Y., E. P. Dutton & Co., 1933. 315 p., illus., 9 x 6 in., cloth, $5.75. The second volume of this text is devoted to electricity and optics. In it, as in the preceding volume, the subject matter has been selected to present physical theory as a coherent logical unity. Electrostatics, magnetostatics, the fundamentals of electrodynamics, thermoelectricity, Maxwell's theory, electron theory, dispersion, scattering of radiation, etc., are discussed.

Engineering Societies Library

29 West 39th Street, New York, N.Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

G-E Reports Business Increase in 1933.—Orders received by the General Electric Co., during the year 1933 amounted to $142,770,791, compared with $121,725,772 for 1932, an increase of 17 per cent, according to a recent announcement. Orders for the quarter ended December 31 amounted to $37,985,790, compared with $27,351,658 for the last quarter of 1932, an increase of 39 per cent. The company continued to experience an increase in the number of its stockholders during 1933. The gain was considerably smaller than in recent previous years, but it nevertheless enabled the company to close the year with the largest number of stockholders it has ever had—188,316.

New Canadian Agency for Brown Boveri.—A new company, the Swiss Electric Co. of Canada, Ltd., has been formed, which has an exclusive arrangement to distribute in Canada the products of Brown Boveri & Co., Ltd., of Switzerland, the Micafil A.-G., and other companies. Headquarters will be temporarily in the offices of Griswold & Co., Ltd., the former distributors of Brown Boveri products.

Asbestos Companies Merge.—The Ambler Asbestos Shingle & Sheathing Co. and the Keasbey & Mattison Co., both of Ambler, Pa., have merged, and a controlling interest has been acquired by Turner & Newall, Ltd., of Great Britain. The latter firm and subsidiaries constitute one of the largest factors in the asbestos and magnesia business in the world. The enlarged business will retain the name of Keasbey & Mattison Co., remain under American management, and American capital will continue to be largely represented, according to the announcement.

New Insulating Materials Agency.—S. T. Rodgers, for the past 16 years connected with the Sherwin Williams Co. in the capacity of insulation engineer for the development and sale of insulating varnishes and compounds, has established a manufacturers' sales agency at 3351 Norwood Road, Cleveland, and will handle a complete line of electrical insulating materials. The territory covered will consist of Ohio, western Pennsylvania and eastern Indiana and Michigan.

Incandescent Lamp Sales Increase in 1933.—A preliminary estimate of the number of lamps sold in the United States during 1933 indicates a total of 616,000,000 for both large and miniature lamps, representing an increase of more than 11 per cent over the sales in 1932. The use of carbon filament lamps, as in previous years, continued to decrease. Among the developments of the year in lighting equipment noted by the General Electric Co., were the introduction of a three-light Mazda lamp, a high-powered "movie flood" lamp, new sizes in photoflash lamps, sodium-vapor lamps for highway lighting, hot-cathode positive-column lamps for color floodlighting and the spectacular illumination of the Century of Progress at Chicago.

New Laboratory Super Centrifuge.—The Sharples Specialty Co., 23rd & Westmoreland St., Philadelphia, has developed a new laboratory supercentrifuge which makes available an extremely high, efficient separating force for the sedimentation of solids from liquids, the clarification of liquids and the separation of immiscible liquids occurring as mixtures and emulsions. These operations are performed continuously. Liquid material is introduced into the rotating bowl of the machine where it is subjected to a separating force as high as 62,000 times the force of gravity. It is then discharged continuously. The frame of the new models is similar to the large size Sharples commercial centrifuges so that the turbine head or motor drive head can be installed. The new machine can be equipped for either steam or compressed air turbine drive or motor drive. It has wide application in industry, in laboratory control work, research work for the development of new processes, etc.

Voltage Adjusting Device for Electrical Appliances.—Designed and manufactured by The Acme Electric & Mfg. Co., Cleveland, the "variable voltage adjustor" permits the regulation and adjustment of the primary line voltage from either below or above normal to the proper operating voltage of electrical appliances, radio receivers, refrigerators, etc. Similar in construction and appearance to an ordinary step-down transformer, a series of taps has been created within the case and a manually operated dial provides the necessary regulating medium for control. A sensitive and extremely accurate instrument indicates the secondary voltage in connection with the regulation from the operating dial. The variable-voltage adjustor is well suited for service shop use being light, handy, and affording a means of testing appliance and electrical products under a series of low-voltage and over-voltage conditions.

Old Engineering Company Changes Name.—The name of W. S. Barstow & Co., Inc., has been changed to E. M. Gilbert Engineering Corp., according to an announcement from the company's headquarters, Reading, Pa. E. M. Gilbert, whose name is given to the corporation, entered the public utility field in 1907. In 1916 he became vice-president and chief engineer of W. S. Barstow & Co., and in 1929 was elected president. The Barstow company was incorporated in 1906 to function as a centralized engineering, construction and management company for various utilities, and has acted also in a general consulting capacity in a wide variety of construction and operating problems. Except for its change of name, the corporation will continue with its same policies, and personnel. It has to its credit the completion of many outstanding power plants, including the Gilbert steam station on the Delaware River near Holland, N. J., unusual because of its low fuel consumption—.877 pound of coal per kilowatt hour; also the hydroelectric development on the Saluda River near Columbia, S. C., a project involving the building of the largest earth dam in the world for power purposes.

Trade Literature

Suspension Insulators.—Bulletin 604-H. Describes important developments in suspension insulators. In addition to the more technical data the booklet contains complete catalog listings of the entire O-B line of transmission products. Ohio Brass Co., Mansfield, O.

Hoists. Bulletin RH-1. Describes applications of hoists for every plant and purpose, treating both general and specific problems. Installations are illustrated and diagrams explain simplified design, construction and operation. The Harnischfeger Corp., 4400 West National Ave., Milwaukee.

Arc Welding Handbook.—The seventh edition of this book by C. J. Holslag has been brought up to date with chapters on shielded arc, hammer annealing, flux covered, normalizing electrodes and others. It also contains, in the words of the author "a very interesting explanation of why fusion welding fusions and why steel holds together anyway." Electric Arc Cutting & Welding Co., 152 Jelliff Ave., Newark, N. J.

Motors.—Bulletin 3085, 4 pp. Describes type S, improved split phase motors, with steel field rings, smaller dimensions and quieter in operation, for small pumps and compressors, oil burners, fans, blowers and air conditioners, drill presses, etc., available in $^1/_6$ and $^1/_4$ hp, 1,725 rpm, and $^1/_8$ and $^1/_6$ hp, 1,140 rpm, with resilient or rigid base mountings. The Emerson Electric Mfg. Co., 2018 Washington Ave., St. Louis.

Circuit Breakers.—The Square D Co. has added to its line of industrial circuit breakers a 600-ampere frame, making it complete from 15 amperes to 600 amperes. These breakers are available for 230 volts, alternating current, and 125–250 volts, direct current, as well as in 3 and 4-wire solid neutral and in 575 volts alternating current and 250 volts direct current. The complete listing of the new industrial circuit breaker line will be carried in the company's standard catalog, to be reissued shortly. Square D Co., Detroit.

Cables.—Bulletin, 4 pp. Describes four types of "Trenchlay" cable-power, for all power circuits up to and including 5,000 volts grounded neutral and not over 3,000 volts ungrounded neutral; concentric, for rural extension and series street lighting up to and including 11,000 volts between phase conductors to ground; control, for multiple control and signal circuits not over 600 volts; railway signal, for all types of railway signal service up to and including 750 volts. Trenchlay is a non-metallic cable, designed and developed for direct earth installation. General Cable Corp., 420 Lexington Ave., New York.